A Finite Element Framework for Geotechnical Applications based on Object-Oriented Programming

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Content

ABSTRACT ..... **V**

1 INTRODUCTION **1**

2 MOTIVATION **3**

2.1 INTRODUCTION 3
2.2 PROCEDURAL PROGRAMMING PARADIGM 3
2.3 OTHER PROGRAMMING PARADIGMS 4
2.4 OBJECT-ORIENTED PROGRAMMING PARADIGM 5
2.5 REQUIREMENTS FOR LARGE PROGRAMMING SYSTEMS, OR HOW OBJECT-ORIENTED PROGRAMMING MEETS THE GOALS 6
2.6 SUMMARY 8

3 OBJECT-ORIENTED ANALYSIS: AIM AND FUNCTIONALITY OF THE FE FRAMEWORK IMAGINE **9**

3.1 INTRODUCTION 9
3.2 AIM OF THE FRAMEWORK 9
3.3 DOCUMENTATION 10
3.4 OBJECT DATABASE 10
3.4.1 Introduction *10*
3.4.2 Persistence *11*
3.4.3 Object-oriented database *14*
3.5 DEVELOPMENT ENVIRONMENT 16
3.6 FE KERNEL 17
3.7 GEOMETRIC MODELING 18
3.8 POSTPROCESSING 20
3.9 PROJECT MANAGEMENT 20
3.10 USER INTERFACE 21
3.11 STATE OF THE ART 22

4 OBJECT-ORIENTED DESIGN AND IMPLEMENTATION OF THE FE FRAMEWORK IMAGINE ... **25**

4.1 GUIDELINES 25
4.2 ARCHITECTURE OF IMAGINE 26
4.3 PROJECT AND RESOURCE MANAGEMENT SUBSYSTEM 27
4.3.1 Project view and control *27*
4.3.2 Geometric modeling *29*
4.3.3 Project resources and their management *32*
4.3.4 Analysis and task control *35*
4.4 FE MODELING SUBSYSTEM 38
4.4.1 Overview *38*
4.4.2 Modeling classes and field variable classes *39*
4.4.2.1 Overview 39
4.4.2.2 Element concept 42
4.4.2.3 Node and degrees of freedom (DOF) concept 45
4.4.2.4 Load concept 46
4.4.2.5 Constraint concept 47
4.4.2.6 Material concept 48
4.4.3 Numerical classes *49*
4.4.4 Global representations *51*
4.4.5 Basic classes *53*

5 DESIGN AND IMPLEMENTATION OF THE USER INTERFACE 55
5.1 INTRODUCTION 55
5.2 WORKBENCH APPROACH 55
5.2.1 Overview 55
5.2.2 Kinds of workbenches 57
5.2.3 Layout of a workbench 58
5.3 FEM MODELING WORKBENCH 59
5.3.1 Geometric resources at the project level 59
5.3.2 Modeling resources at the project level 62
5.3.2.1 Design of the interface 62
5.3.2.2 Resource forms 64
5.3.3 Meshing 68
5.3.4 Conclusions 72
5.4 FEM TASK WORKBENCH 72
5.4.1 Overview 72
5.4.2 Task manager 72
5.4.3 Task objects 75
5.4.4 Command objects 77
5.4.5 Conclusions 80
6 EXAMPLE 81
6.1 INTRODUCTION 81
6.2 SECTOR WITHOUT LINING 81
6.3 SOLID MODEL VERSUS SUPERELEMENTS 89
7 CONCLUSIONS 93
APPENDIX 1: FROM PROCEDURAL TO OBJECT-ORIENTED PROGRAMMING 95
APPENDIX 2: SOFTWARE LIFE CYCLE 97
APPENDIX 3: THE DOCUMENT-VIEW CONCEPT OF THE MFC 99
APPENDIX 4: STYLE GUIDE 101
INTRODUCTION 101
ONLINE DOCUMENTATION 101
NAMING CONVENTIONS 102
REFERENCES 105

Abstract

This publication describes an alternative methodology for finite element programming based on object-oriented techniques. The concepts of object-oriented programming are outlined and it is explained, how this new paradigm facilitates design, implementation and support of large programming systems. Because the knowledge of object-oriented programs is not dispersed in the actual code, but rather localized in structures, the causal knowledge, meta knowledge and constraints may be integrated in a uniform manner. Control structures separate the external level ('what') from the internal ('how') by encapsulating the actual implementation. As programming language C++ is used.

Up till now several object-oriented finite element frameworks have been presented which are partially extendable. However, the extendibility is limited to a few specific directions, e.g. the introduction of new element types or solving strategies. Much less support is available for task control, creation of new material models, configurable field variable types or extensions of the analysis model. No framework is available which is especially designed to cover the problems encountered when dealing with geotechnical engineering. IMAGINE tries to close these gaps.

The nucleus of the Finite Element framework presented relies on abstractions, which include common concepts accepted in mathematics, mechanics, engineering and interactive visualization techniques, and serve as the fundamental object-oriented framework of classes for finite element applications and task management. The aim of the framework was not to include as many features as possible (e.g. a variety of types of finite elements or material laws), but to provide a sophisticated and robust foundation which may be used in the future due to its inherent capabilities of simple maintenance, adaptability to new resources and extendibility, especially directed towards applications in geotechnical engineering.

Based on this framework an experimental finite element application for geomechanics is presented. Here everything is regarded as an object: loads, load groups, computational tasks etc. Thanks to the graphical user interface under MS-Windows and the rule of non-anticipation on which the objects rely, the handling of the program is straightforward.
Some test examples illustrate its usage.

Keywords: *object-oriented programming, OOP, finite elements, framework, toolkit, C++, geotechnical engineering.*

1 Introduction

As long as there were no machines, programming was no problem at all; when we had a few weak computers, programming became a mild problem, and now we have gigantic computers, programming has become an equally gigantic problem (Dijkstra, 1972).

Typically, development of finite element codes has been started by research organizations. Then the codes have been transferred to private companies, where they have been extended and enhanced. The researchers have been left with a multitude of rather incomplete code fragments, each tailored to a specific topic of interest. Due to advances in programming and because of the conventional, inflexible design, scientists usually could not rely on existing code and had to start practically from scratch for each new research project which extended the current model. Furthermore, for scientific consulting work or for teaching purposes, they used some third party software which was, at least for geotechnical engineering, not one hundred per cent tailored to the specific problem to be solved, but was much easier to handle thanks to an elaborate, comfortable user interface.
Therefore, research organizations would benefit from a Finite Element framework[1] for geotechnical applications which should provide (in an easy way)

- extendibility,
- reusability,
- understandability from the programmer's point of view,
- maintainability,
- a basic set of the most often used features, and
- a satisfactory user interface which may be complemented by third party software.

Numerical analyses just provide a limited contribution to the design process in geotechnical engineering. Equally important aspects are geology, measurements in situ and in the laboratory, and mainly experience. On the other hand the fundamentals of modeling in numerics are quite demanding. Even the most important material, the rock or soil, cannot be chosen, but is just encountered. It is not unusual that the introduction of just one new model parameter, e.g. swelling behavior, may lead to a multitude of research works. For these reasons private industry is commercially not willing (or able) to develop Finite Element (FE) programs for solving special problems in geotechnical engineering or research work. However, they agree that they do need novel numerical tools. This is illustrated by a survey of the ASCE-sponsored Underground Technology Research Council (UTRC, 1991) at 50 practitioners of underground engineering companies. The highest priority for research work was assigned to the problem of groundwater inflow into tunnels, which requires investigations with both numerical models and field observation.
Therefore, special-purpose FE codes have to be developed by research groups.

[1] A framework is a collection of classes that provide a set of services for a particular domain (Booch, 1994), e.g. for building compilers.

Additionally, for research organizations in geotechnical engineering it is absolutely necessary to get some feedback from industry, if they should not loose the practical basis in their research projects. Therefore, they are strongly interested in keeping up the exchange of experience with practicing engineers, which is guaranteed if industry uses their programs.

2 Motivation

2.1 Introduction

Since many years, professionals have been aware of the so-called software crisis (Wirfs et al., 1990). The main problem of large software systems is the great effort necessary for the continuous support of software, i.e.

- maintenance, e.g. debugging,
- adaptation to new resources (e.g. compilers or hardware), and
- extensions.

This is particularly true for FE programs. An increasing demand on new analytic capabilities, constitutive models and easy-to-handle graphical user interfaces requires the introduction of new design methodologies. However, as a matter of fact, current textbooks on the Finite Element Method (FEM) are still very similar to those of two decades ago. This is also illustrated by 60% of all codes of engineering software being written in FORTRAN, about 6% in C and 0% in object-oriented C++ (Smith, 1994). Only a handful of research projects have been undertaken in the last few years to overcome these limitations.
The current section will highlight some of the reasons why conventional programming paradigms coupled with programming languages introduced 40 years ago are not able to help solving the software crisis, and which perspectives seem to be most promising to overcome this problem.

2.2 Procedural programming paradigm

Practically all current FE codes of significance rely on the FORTRAN programming language, an exponent of the procedural programming paradigm. Therefore, the current subsection is limited to the discussion of FORTRAN. Furthermore, it is assumed that the nomenclature as outlined in "Appendix 1: From procedural to object-oriented programming", is known.
A procedural program may be viewed as a set of algorithms, controlled by an imperative language (Miller, 1989). Disregarding technical aspects such as the limited syntax of e.g. FORTRAN, which partly have been overcome with the latest version (FORTRAN 90), the basic problems of procedural programming stem from the following inherent conceptual shortcomings:

- just one level of functional abstraction[1],
- no data abstraction,
- no localization of data,
- no information hiding,
- semantic breaks.

The design of the FORTRAN language does not envisage any abstraction or structuring, except the decomposition in subroutines. However, subroutines provide just one and only one level of process or functional decomposition (e.g. input, solve, reading data from an array etc.). Therefore, e.g. task management, user interaction, numerical algorithms and data representation are all handled at the same level. Furthermore, they are not handled directly as concepts, but concentrate on low level implementation details (Baugh and Rehak, 1989). Procedural

[1] Abstractions include two different aspects: an "abstraction" idealizes an entity by describing its most essential properties only, and it hides *what* capabilities the entity possesses from *how* they are reached.

programming relies on *how to* compute (retrieve geometry, material properties etc., and then compute stiffness), instead of the more understandable declarative approach of *what to* compute (ask the element to compute its stiffness).

Due to the missing abstraction levels, information hiding is rarely used. Welcome exceptions may be the concentration of low level plotting commands in a few routines or a difficult to implement memory management (Fritz, 1983).

For data no corresponding decomposition or localization may be defined. Only simple data structures are available, which must be put at the subroutines disposal either as globally accessible (and changeable) COMMON-blocks, or as long and involved parameter lists, which are prone to errors and side effects. It is rumored that such a side effect cost a company US$ 1.6 billions due to one single incorrect character (Berard, 1993, p.41).

Information hiding with regard to data is practically not achievable. Data are just representations of values (e.g. coordinates), but not concepts e.g. of a node. They do not possess any additional knowledge. Therefore, the program flow must be strictly sequential, guided by a rigid control strategy.

Semantic breaks occur in two circumstances:
First, already in the stage of analysis, concepts are replaced by functional decomposition or/and a data-oriented composition (Groth et al., 1994). In the design phase the individual entities are assembled to collections of similar subject or behavior. During implementation the same entity may include code ranging from a very high down to a very low complexity or abstraction level. And the test phase must follow the semantics of the three foregoing phases. Obviously, semantic breaks occur all along the life cycle of a project.
Second two different programming paradigms are often used: one for the engineering part of the software and the other for the database management system (DBMS) (Yu and Adeli, 1993). Conventional DBMSs of large FE systems usually just rely on the flat relational data model.
Semantic breaks lead to inhomogeneities in design and implementation, which impair readability, localization of tasks and recursive development.

2.3 Other programming paradigms

In view of the limitations of the procedural programming paradigm research concentrated on finding a new conceptual architecture which should lead to programs which are easy to understand and modify. Some of the perspectives at hand are:

- Database Management Systems: in view of the large, complex data structures of FE systems this approach puts the DBMS in the center of interest (Felippa, 1985). However, engineering parts must still be added, which leads to the above mentioned problem of global accessibility of data and inhomogeneity.
- General Programming Systems: this concept is based on collections of subroutines, where each set performs an independent computational task (Mo, 1978). This is less a new programming paradigm, than an improved programming technique.
- Logic or Constraint-Oriented Programming: a program consists of a set of rules which are processed by an inference engine (Buchanan, 1983). Logic programming is often used when metaknowledge is involved (rules of thumb), but less for mathematically precise applications

like the nucleus of an FE program. However, even for FEM many problems remain which may be solved with logic programming, e.g. abstraction of the real world, or task control.

- Functional Programming: a program is viewed as a flow of data through recursive function calls. This concept should not be confused with dataflow hardware, even when this type of hardware seems more suitable to host this technique compared to a purely sequential Von Neumann machine (Dwyer, 1989). Although taking into account that even FE programs have been written with purely functional languages like Lisp (Baugh and Rehak, 1989) or SASL (Dwyer, 1989), it seems more research is needed to prove their applicability with respect to efficiency and algorithm design.
- Generic Programming relies on classifying abstract software components and their behavior which results in a standard taxonomy (Stevens, 1995). The emphasis is on the semantics and semantic classification, while object-oriented languages place stronger emphasis on how to build class hierarchies, and not what should be inside. Main application domains for generic programming are expected in list management, search algorithms, databases etc., but less in specific mathematical applications as the FEM. An outflow of generic programming, the so-called Standard Template Library (STL) has recently been approved by the ANSI/ISO-committee as part of standard C++, therefore the future will enable inclusion automatically.

2.4 Object-oriented programming paradigm

The remaining and most promising approach to discuss is the object-oriented programming paradigm. This paradigm is more the result of an evolutionary process, than of a revolution (c.f. "Appendix 1: From procedural to object-oriented programming"). Here it is assumed that the underlying theory is known (c.f. Lippman, 1998). Just a few characteristics will be outlined, which either seem very important to us in the actual context, or which up till now have not found a unique definition. As the FE framework IMAGINE is written in the programming language C++, the way of understanding terms will adopt to that of the C++ community.

Object-oriented programming (OOP) shall be defined as a paradigm relying on

- data abstraction, i.e. abstract data types or classes,
- inheritance, and
- polymorphism, i.e. dynamic binding.

The authors of this report do not request data type completeness as a prerequisite for OOP, as some authors of pure object-oriented languages do.

A class is a template of a self-contained computational entity and defines usually the analog of a real world item, but may also define an abstract concept (e.g. an operation). It possesses attributes (so-called member data or instance variables) and may respond to or may be subjected to actions. Encapsulation enables to hide information inside a class. Thanks to different levels of abstractions information hiding may vary in degree (to the outside of a class or even inside a class hierarchy).

Instances of classes are called objects. Also instances of parameterized classes are called objects, i.e. they are not treated as so-called metaclasses as in other languages. Objects communicate with each other by sending messages, i.e. executing their member functions or so-called methods.

Inheritance allows the creation of hierarchically structured class systems, with different levels of concern or abstraction. Four classes of inheritance relationships may be distinguished:

- Specialization: from a base class a specialized subclass is derived, which redefines some properties of the base class. The base class captures the similarities between objects, the subclass the differences. The base class is said to be a generalization of its subclass. Inheritance allows one to exploit the commonality between classes without introducing redundancy.
- Extension: similar to specialization, but some properties are added to the derived class.
- Modification: similar to specialization, but some properties of the base class are not inherited. They are hidden or masked out in the derived class.
- Aggregation: complex objects may be constructed by embedding other objects in a class.

Polymorphism includes both compile-time and run-time polymorphism. The former is also called early binding, the latter late binding (c.f. "Appendix 1: From procedural to object-oriented programming"). Polymorphism enables a higher level of abstraction in software design, thereby enhancing understandability and maintainability.

2.5 Requirements for large programming systems, or how object-oriented programming meets the goals

Under large programming systems codes with tens of thousands of lines are understood, as opposed to small programs with several thousands of lines, or very large systems, with many hundreds of thousands or millions of lines. The latter may present completely different problems (e.g. communication between development groups), which are not covered here.

The most important requirements for a large FE system are the following:

- simple software support, i.e. easy maintenance, adaptation to new resources and extendibility,
- reusability, implying understandability (readability, traceability, learnability), homogeneity and portability,
- reliability, which designates the probability with which software does not cause the failure of a system, or lead to incorrect results,
- software security, which means the degree to which software protects itself from unauthorized actions,
- software safety, i.e. the probability that even an unintended usage does not lead to a mishap (hazard).

These requirements are met by OOP in the following way:

- Localization of data facilitates maintenance through the absence (to a large extent) of side effects. However, emphasis must be placed on minimal object coupling to reach this goal. Inheritance and parameterized types improve adaptability and extendibility, in that they do away with copying of source code as is usual in conventional approaches. The declarative approach of OOP seems to be nearer to human nature than the procedural one. Uncoupling of flow control from engineering algorithms facilitates future combination with techniques of artificial intelligence.
- Reusability is perhaps the most promising feature of OOP. This implies not only reusability per se, i.e. for other projects, but also with regard to major extensions of the current project. The Alpha and Omega of reusability is understandability. Readability in the small may be achieved by standardized class headers, listing usage, external relation and position in the class hierarchy. Readability in the large, traceability and portability are achieved by several levels in the abstraction hierarchy, each of which treating homogeneous objects of interest.

  Learnability of OOP systems is supported by class hierarchies which group topics, and polymorphism which reduces the number of function names to remember. Abstract data types let the programmer work at higher levels of abstraction.

  Thanks to the iterative or even recursive design process common in OOP (Berard, 1993), it is usual to condense out abstract base classes and possible frameworks all along the life cycle of a project, thereby creating new class hierarchies which lead to a cleaner and better design. Larger object-oriented applications will end up consisting of layers of frameworks that cooperate with each other (Gamma et al., 2000).
- Software reliability, security and safety are supported by transferring responsibility from the programmers to the program: e.g. constructors guarantee, if correctly applied, that no undefined variables exist, and destructors, that the resources are freed whenever they are not needed anymore.

However, there are also some drawbacks of OOP. An important one is, that the demands on the developers are substantially higher. In the field of engineering developers are often not professional software engineers, so they feel discouraged by the complexity of OOP and the steep learning curve. Learning an OOP language means not only learning a new language, but getting acquainted with a new way of thinking. This may be the reason that most FE programs have been and are still being written in FORTRAN, thereby wasting resources as outlined above.
At this point it should also be noted, that the power of OOP is not only based on the tools and techniques provided by the underlying programming language, but also on the attitude of the developers. It is said from Smalltalk programmers, that they need more time to browse through existing classes, than to code their own ones. An attitude which is certainly a proof for reusability, and which is not common for conventional programmers. The OOP paradigm allows the introduction of abstractions, but they are only exploited to their full potential by programmers with an obsession for simplicity and perfection (Johnson and Foote, 1988). Unfortunately it is also possible to program with an OOP language in a style similar to FORTRAN or C.

When choosing OOP there still remains the choice of the programming language. This is partly a matter of taste and will therefore not be discussed here to its full extent. Suffice to say that the programming language C++ was chosen primarily because of its widespread usage, which guarantees its continuity in the future. Additionally, the following technical aspects support this decision:

- efficiency: several comparisons report similar efficient code for C++ as for FORTRAN, which, up till now, was considered to lead to the most efficient code for scientific applications (apart from the Assembler language). This is illustrated by Fig. 1, where the deviations of the CPU-times of C and C++ with respect to FORTRAN are displayed. The differences are quite small. The influence of the hardware platform being used on this relationship may be bigger than the inherent difference between C, C++ and FORTRAN itself.
- modern operating systems themselves are usually largely written in C or its superset C++. Therefore, using C++ allows one to take advantage directly of the existing highly optimized operating system library.
- for the chosen development environment Microsoft (MS)-Windows a powerful framework in C++ exists, the MS-foundation class library (MFC), which provides an architecture for abstracting the user interface and other essential components of a Windows application. Using this framework enlightens programming considerably.

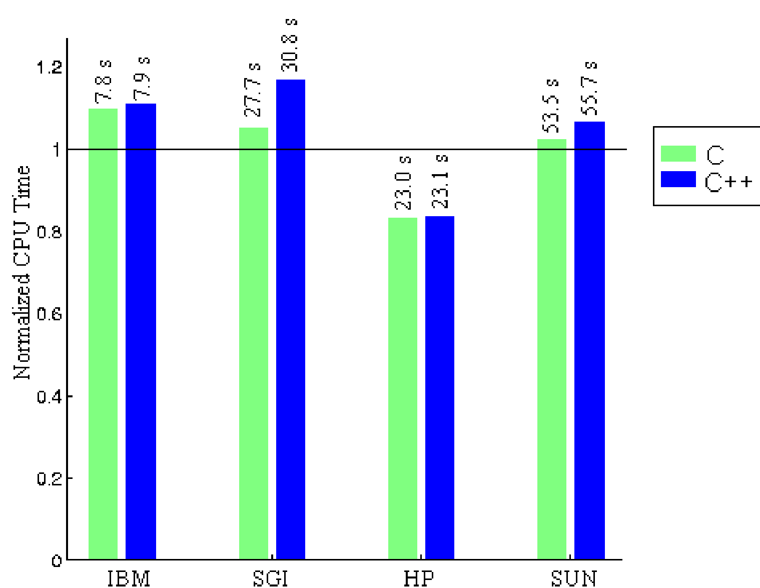

Fig. 1 CPU times of a matrix by vector product for C, C++ and FORTRAN (normalized to FORTRAN) after Bruaset et al. (1996).
Computation: 1'000 multiplications of a sparse matrix of 1'000 rows with a vector
Platforms: IBM RS6000/50, Silicon Graphics Indigo, HP 9000/735 and Sun SPARCstation 10/512

2.6 Summary

FE programs in the field of Geotechnics involve a large number of topics, including modeling, mechanics, mathematics and visualization. The software itself should satisfy extreme efficiency requirements. It should enable the casual user to define his or her model in an easy and foolproof way, and the programmer to extend an application program to include a specific feature with a minimum amount of work and even more important, with minimal side effects.

OOP offers new possibilities from both the conceptual and the technical point of view.

3 Object-oriented analysis: aim and functionality of the FE framework IMAGINE

3.1 Introduction

The life cycle of software viewed in the light of the object-oriented paradigm comprises

- Object-oriented requirement analysis (OOA),
- Object-oriented design (OOD),
- Object-oriented programming (OOP),
- Testing, and
- Maintenance.

A definition of these individual steps may be found in "Appendix 2: Software life cycle". In the current and the following sections they are treated more closely with respect to the FE framework.

In the analysis phase the external characteristics of the system which are visible to the user (programmer) and the key abstractions are defined. Additionally, sources of information are identified which may help to solve the task in hand, and an overall description of the whole system is given.

3.2 Aim of the framework

The objectives of the FE framework IMAGINE (**I**ntegrated **M**odeling and **A**nalysis in **G**eotechnics by f**in**ite **E**lements) are twofold:

- provide scientists and practicing engineers in the field of geotechnical engineering with the means to develop applications tailored to their requirements,
- development of an example application for geomechanics for a de facto proof of the applicability of the framework. Furthermore, this application might be used by students, scientists and practicing engineers.

The first aim requires as mentioned above

- extendibility (with regard e.g. to statical or physical modeling, algorithms and task management),
- understandability from the programmer's point of view,
- maintainability,

and the second aim

- a basic set of the most frequently used features,
- a satisfying user interface.

It must be realized in advance that it is not aimed to develop a universal framework which may be used for all kinds of FE application. An example of a universal FE system is NASTRAN which required hundreds of man-years for development, further hundreds for maintenance, and still cannot satisfy the specific needs of each engineer.

3.3 Documentation

As a red thread documentation spans all the life cycles of a project. It is a vital factor for the understandability of a program. This starts already at the analysis and design phase, where it has been suggested to summarize the characteristics of each class on so-called class cards (Wirfs et al., 1990). These list besides the position of the class in the hierarchy also the functionality and the necessary cooperation (relations to other classes) to achieve it. A similar card is created for each subsystem[1] specifying the functionality and to which class its achievement is delegated. During the life cycle these cards are refined and extended to textual specifications. A similar approach is propagated by Booch (1994), which replaces the cards by clouds with various types of outlines indicating various states and relations. Additionally, he introduces sets of diagrams for objects, modules and processes.
The variety of methods for describing software modeling is unified and standardized by the Unified Modeling Language (UML), c.f. Oestereich (1998). The UML is a language and notation for the specification, construction, visualization and documentation of software systems. It uses several diagram types, the most important of which are diagrams for classes, states of classes, sequence and collaboration of objects, use cases and components.

For IMAGINE which, according to the definition above, falls into the category of a large (as opposed to "very large") system, these procedures did not prove to be adequate, perhaps because of its limited size. Therefore for producing the documentation we distiguish the following phases:

- Object-oriented analysis: documentation of the systems aim and the semantics of its functionality.
- Object-oriented design: documentation of the vision and the details of the architecture and its key abstractions.
- Object-oriented programming: it is an old experience that it is very difficult to motivate programmers to comment their code in separate manuals. Additionally, such manuals are often not up to date and therefore of limited value. Therefore, online descriptions inserted in the code itself are recommended. This is the place where the programmer works, and where he will effectively add or change comments easily when changing the code. Together with a class browser these descriptions must be sufficient for a new programmer to understand the whole programming system.
- Testing and maintenance: a suite of test examples serves to check firstly the correctness of the initial code and secondly the stability along the maintenance phase.

3.4 Object database

3.4.1 Introduction

Various data models may be used for storing and accessing the data of an FE system. The widespread *relational model* relies on relations with attributes which in essence are represented in two-dimensional cross-linked tables of fixed record length. Another frequently applied model is the *indexed sequential* one which allows to access records of variable length through indexes. Both models are based on relatively rigid record structures and are value-oriented.
In contrast Smith and Smith (1977) postulated already before the emergence of OOP a model anticipating exactly the idea of the OOP paradigm. They postulated a database design based on the two abstraction mechanisms:

[1] A subsystem is a conceptual entity which is defined (Wirfs et al., 1990) as an aggregation of classes and possibly other subsystems which is responsible for a set of functionalities.

– generalization: individual objects are represented at a higher level of abstraction,
– aggregation: individual objects are grouped together to higher level objects.

Models are then formed by sets of generalization hierarchies intersected with sets of aggregation hierarchies. Unfortunately at that time no programming language was available tailored explicitly to this paradigm. The advantage of this design is that arbitrary entities may be modeled together with their relations, which make it much easier to describe highly interrelated engineering systems. Furthermore, it smoothly fits into an object-oriented program avoiding semantic breaks.
Because C++ does not include the ability to store and retrieve persistent objects as an inherent part of the language, the problem of persistence will be treated first, independently of the problem of designing the classes which define persistent objects.

3.4.2 Persistence

The basic idea of *persistence* with regard to objects is that an object should be able to write its current state to persistent storage. However, introducing persistence in C++ is not an easy matter because of the variety of entities which may form an object. Such entities may be other objects, pointers or references to objects, pointers to virtual functions etc. In C++ objects are uniquely identified by their addresses. Because these addresses are changed after saving and restoring objects and because C++ does not support the notion of an object identity, a system must add an identity key to each object created to support persistence. This identity key is usually defined by the objects class name and some unique number per class. Several approaches exist to cope with these problems.

The simplest approach is avoiding all problems by using an *object-oriented wrapper* around an existing relational database (c.f. VISTA++, 1991). However, this also reduces the benefits one would gain with an object-oriented database.

Another approach is to extend C++ itself and write a *preprocessor* which translates it back to standard C++ (c.f. POET, 1993). This preprocessor additionally creates a class dictionary which enables e.g. following the connections of aggregated pointers to other persistent or not persistent objects. Object identity is assigned automatically by the system. The advantage of this fully automatic approach is that, opposed to some other solutions presented below, besides some keywords the programmer does not usually have to write additional code on how to save and restore the objects. An exception is if a type contains variable length data which cannot be derived from the declaration. In this case the specifications of the type must be included in a special type manager. The disadvantage of the automatism is first its overhead, and second that it needs a special preprocessor, which may lead to problems when using an integrated development environment.

The following approaches may be characterized by the idea, that the persistent classes must participate in their own persistence.
Perhaps the first implementation of persistence of objects in standard C++ is available in the *NIH class library* of the National Institute of Health in Maryland, U.S.A. (Gorlen et al., 1990). The precondition is that persistent objects must be derived from a common base class **Object**[1], which manages the identity of objects. The programmer is then responsible for adding to each of his classes (which should be made persistent) two virtual member functions with the actual code

[1] In this report all class names and methods are written in bold characters.

firstly for calling the corresponding member function of its base class and secondly for reading and writing all member data. Pointers to user defined objects are originally not supported, but they could easily be added.
The NIH class library is a comprehensive framework of about 17 thousand lines of source code which extends the functionality of C++ similar to the one provided by Smalltalk-80 (Goldberg and Robson, 1983), i.e. persistence is just one of the features of the framework. Therefore, the overhead just to take advantage of persistence would be far too big. Perhaps it would be possible, although quite costly, to extract and use just a subset responsible for persistence.

A similar approach, but limited to the problem of persistence, is offered by the *PARODY class library* or database (Stevens, 1992). The precondition is that persistent objects must be derived from a common base class named **Persistent** In contrast to the NIH library, reading and writing are initiated by the constructor and destructor in a sophisticated way (c.f. Fig. 2): e.g. the destructor calls function **SaveObject** of class **Persistent**, which calls the user implemented function **Write**. There admissible data types (e.g. basic types) are saved individually with **WriteObject**, other types with **SaveObject**. To improve efficiency the list of admissible data types may be extended at will. In this way the types of data to be made persistent are not limited and include pointers and references to other objects, pointers to virtual member functions etc.

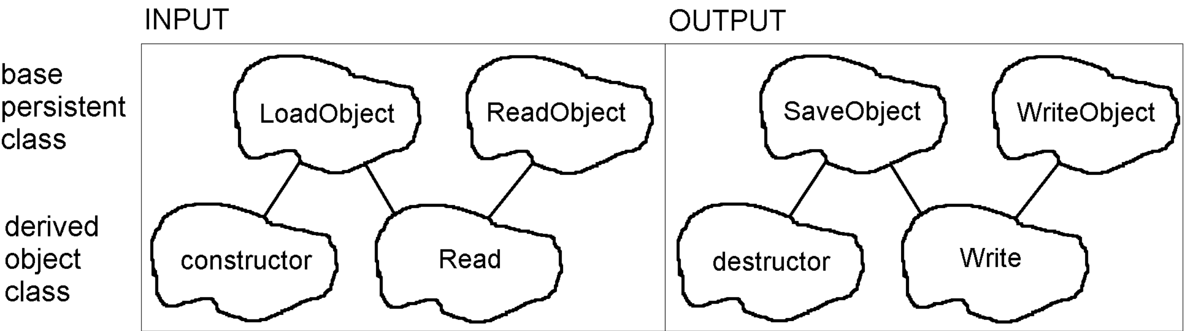

Fig. 2 Object persistence flow (after Stevens, 1992)

The object's identity is defined by its class name and the embedded primary key to be specified in the constructor. With this identity the built in database management system enables navigating the object database and e.g. retrieving individual objects in a specific sequence. When adding, changing or deleting objects via the database management system it automatically checks for violation of class relationship integrity.
PARODY seems to be the most powerful approach compared with its simplicity (it comprehends about 2 thousand lines of source code only). One drawback may be (which is true for all similar procedures) that the classes must be derived from one common base object. If e.g. one would like to use features of the Microsoft Foundation Classes, multiple inheritance would be necessary which firstly should be used judiciously (Meyers, 1998) and secondly may not be available (see below). However, the first statement may be mitigated because it refers mainly to the problems when using the so-called diamond layout of multiple inheritance, which does not apply for this case.

The *Microsoft Foundation Classes Library* MFC (Microsoft Visual C++, 1993) enable similar capabilities with respect to persistence[1]. The precondition is that persistent objects must be derived from a common base class **CObject**, which, by the way does *not* support multiple inheritance. Analogous to the NIH class library, for each class a function **Serialize** must be overridden which first calls its base class function **Serialize** and then actually reads/writes all member variables. The MFC library uses an object of the **CArchive** class as a type safe intermediary between the object to be serialized and the storage medium. The object's identities are automatically managed by **CArchive**.
MFC also supports the persistence of pointers but only for pointers pointing to objects derived from **CObject** (i.e. every pointer in those objects must also point to **CObject** derivatives, and so on).
The only methods available are basically **ReadObject** and **WriteObject**. No navigational features are available, i.e. objects must be retrieved in the same order in which they have been stored. In practice the persistence feature of the MFC library may only be used for reading/writing the whole bunch of data at once. Typical interfaces of this are the *Open* and *Save* commands in the File-menu.
The MFC library provides additionally database classes designed to access any database for which an Open Database Connectivity (ODBC) driver is available. Such drivers exist typically for a variety of record-oriented databases, e.g. relational databases. However, none are known to the authors for object databases, and it is doubtful if they will ever be available due to the completely different organization of the database. Therefore, the database support (in contrast to the persistence support!) of the MFC library is not used in the present work.

The *FE framework IMAGINE* just needs limited database features. E.g. object sorting and navigation through the database are dispensable. The main emphasis lies on making data persistent at the end of a session. During a session accessibility is important: storage, i.e. memory management is delegated to the operating system.
As development environment MS-Windows (see below) has been chosen, together with MS-Visual C++ and its MFC library for the user interface. Because the MFC library's base class **CObject** does not support multiple inheritance, usage of e.g. PARODY is excluded. Therefore, IMAGINE is based on the serialization support of the MFC library for implementing object persistence.
From this example it may be seen how available resources, e.g. the compiler, may influence architectural decisions.

[1] The MFC call persistence "serialization", probably because the data are written to a disk in a serial fashion.

3.4.3 Object-oriented database

No consensus exists on the definition of an *object-oriented database*. A narrow view could define the database as the disk or memory file to where the persistent objects have been written. A more usage-oriented view, which is used for this FE framework, defines the object database as the set of all persistent objects which may be written to and retrieved from secondary storage. Designing the classes which define persistent objects replaces the conventional database design. The advantage is that the actual program implementation and the database design all take place at the same level of abstraction. In this way problems of integrity of the data (e.g. objects with the same identity should not be stored twice, or objects which are still referenced should not be deleted) and of consistency (e.g. redundant information should not be contradictory) are treated in a natural way together with the normal class design.

The object database should include three levels of abstraction:

- individual objects: instances of classes which should reside on the heap (and not the stack) to avoid deletion when going out of scope,
- collections: a collection object is a set of individual object instances,
- database manager: in the case of the MFC library a **CArchive** object which allows storing and retrieving of objects.

All individual objects which should be stored in the database must be made persistent as outlined above.

Because in FE analyses large amounts of data may result, it is favorable to group them by incorporating them (actually just pointers to them) into collections.

The bulk of persistent data of the framework may be grouped into two categories:

1. collections of sequential objects where the main emphasis lies on easy and fast retrieval,
2. collections of objects where the main emphasis lies on easy and fast insertion and deletion of individual objects.

The MFC library provides three differently organized collections:

- lists: the list class provides an ordered, non-indexed list of elements (implemented as a doubly linked list). A list may be accessed bi-directionally and inserts and deletes may be performed anywhere without undue performance penalties. However, searching a specific element is quite slow.
- arrays: the array class provides a dynamically sized, ordered, and integer-indexed array of objects. Access is a matter of subscript operation and is therefore very fast. Insertion and deletion of elements in the middle is slow because they involve shifting remaining entries. Also searching a specific element is slow.
- maps (also known as dictionaries): a map is an unordered collection that associates a key object with a value object. It is one subgroup of a so-called associative container (a set would be another). Searching and inserting elements in maps is very fast, however no duplicate keys may exist.

Collections of sequential objects are usually accessed in sequence or by a simple index; new objects are appended at the end. The number of objects is fixed or at least does not vary often. Objects are usually identified by specific attributes, e.g. a (finite) element is characterized by its number. However, searching for individual objects based on such attributes is the exception. The collection type tailored to this usage is the array. Prominent examples of arrays contain element and node objects.

Insertion of objects in arrays is cumbersome, because the whole part after an inserted entity must be shifted one place. If insertion of new objects is prevalent and the number of objects varies dynamically it is better to use lists. Lists will be heavily used e.g. for dynamically created sets of output data in some node groups, or for a list of tasks to be executed defined interactively by the user.
From a logical point of view lists may further be subdivided into two groups: the first contains classes defined by a unique key. They may be searched and compared very easily based on this key. The second group contains collections of different classes all with the same, but not unique key. An example may be a specific material model composed of a bunch of classes describing the properties.

Maps are often used for relational databases, e.g. for sorting a set of records based on an index. At the moment no need for maps is recognized for the FE framework.

The MFC library provides the following list and array classes:

Collection	Lists		Arrays	
Content	Template-based	Not template-based	Template-based	Not template-based
arbitrary objects	CList		CArray	
CObject pointers		**CObList**		**CObArray**
arbitrary pointers to objects **)	CTypedPtrList		CTypedPtrArray	
*void pointers *)*		***CPtrList***		*CPtrArray*
CString objects		CStringList		CStringArray
BYTE objects				CByteArray
WORD objects				CWordArray
DWORD objects				CDWordArray
UINT objects				CUIntArray
*) *void pointers may not be serialized* **) *may only be serialized if they are based on serializable objects*				

Note that the not template-based classes are carried on for historical reasons only. When the IMAGINE project has been started templates had not yet been included in the standard for C++. It may be seen that two of the not-template based classes do not support persistence.

A special problem may arise when extending persistent storage for cross-platform portability. The main problem lies in coping with the byte-ordering differences of various platforms. However, with some extra measures, this goal may also be achieved (Cullens, 1995).

3.5 Development environment

Developing a text-based application does not present any special problems with regard to the platform where it should run. However, nowadays, because an application relies heavily on graphics and an interactive graphical user interface (GUI), the choice of the platform firstly where it is developed and secondly where it may be run is of prime importance and may have serious consequences. The choice of the platform is a high risk and in the long term may lead to success or a dead end.
There exist basically two approaches for writing portable applications:

- using a toolkit[1] which supports a graphical application program interface (API) and a GUI on various platforms. Prominent examples of this are Neuron Data's Open Interface (Palo Alto CA, U.S.A.) and the XVT-toolkit (XVT Software, Boulder CO, U.S.A.).
- development on one widespread platform and using libraries on other platforms which fully support the whole API of the development platform. The prominent example of this is Wind/U of Bristol Technology Inc., Ridgefield CT, U.S.A., which supports the whole MS-Windows API and additionally the MS-Foundation Class Library.

Toolkits of the first approach typically provide libraries and computer aided software engineering (CASE) tools for various platforms, including tools for memory management, string handling etc. They are often based on the least common denominator of the possibilities of the different platforms. Common features on a platform may not (or not yet) be supported. Implementation of such features may at best lag behind and may present problems with respect to performance due to their implementation at a relatively high level.
Libraries of the second approach allow using the standard development environment (and class libraries) of one platform. The look and feel on other platforms may still resemble the development platform. Specific features of the other platforms are not supported.

Another important viewpoint with regard to the platform to choose is dissemination in the market aimed at. Civil engineers in practice most often use MS-Windows machines. Scientists have concentrated on Unix systems. The number of MS-DOS and MS-Windows systems in the world has been estimated at the end of 1994 to exceed 50 millions (Ovum Ltd., 1994) compared with some tens of thousands of Unix systems. Another important trend meter is the number of applications sold for the various platforms (see Fig. 3).

Since then (1993) MS-Windows has gained a large momentum. Nowadays probably the whole group of MS-DOS must be assigned to MS-Windows. To save investment as development environment MS-Windows (version NT or later) has been chosen. Additionally, the MS-Foundation Class Library (MFC) are heavily used. If the need should arise to run the application on Unix systems a library such as Wind/U should require the smallest investment.

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[1] A toolkit is a set of related classes to provide a specific functionality (e.g. collections).

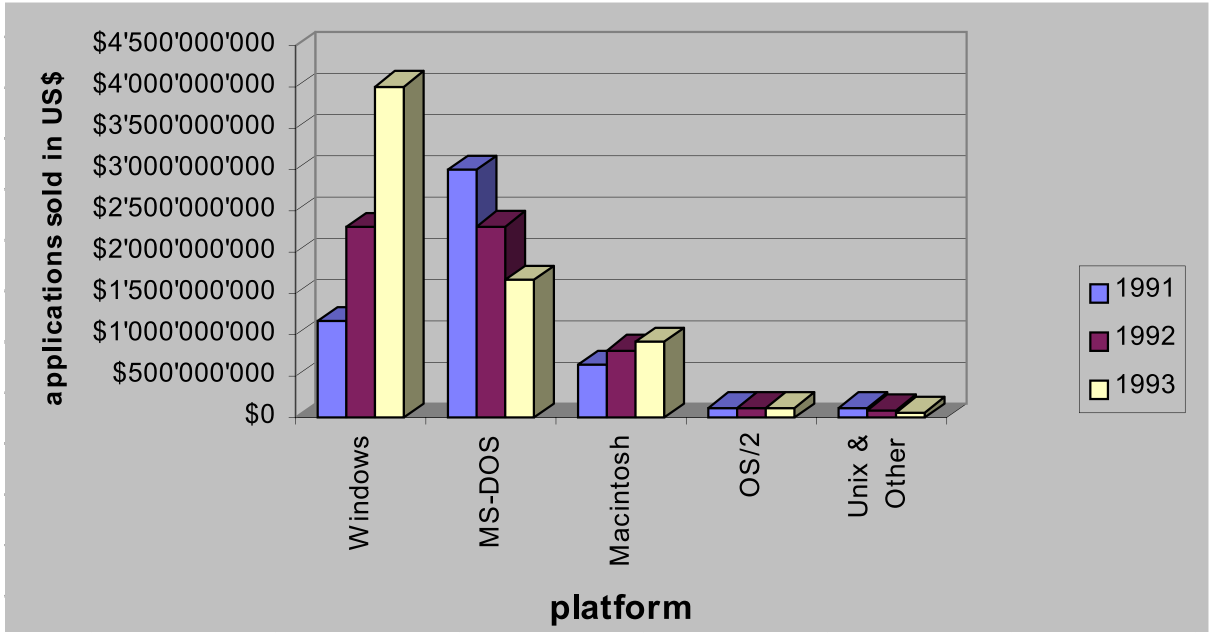


Fig. 3 Value of applications sold worldwide for various platforms (after Software Publishing Association)

3.6 FE kernel

The basic abstractions of the kernel domains of a Finite Element analysis (FEA) model in a direct way the individual parts of an analysis. An FEA includes establishing the local element stiffness matrices and assembling the global one, applying the boundary conditions (loads and constraints), solving the system of equations, and computing secondary field variables (e.g. stress and strain) from the primary ones (e.g. displacements). The prime aim of the framework IMAGINE is to be open for future extensions. Therefore, it is most important to introduce abstractions which separate the individual concerns as far as possible. Thereby abstractions may include both structural aspects and algorithmic aspects.

To begin with, the discretized representation of the physical structure may be abstracted in a fundamental class, in IMAGINE named **FemStruct.** It contains the individual components which form an FE system at the local level. The most important ones are abstractions for the finite elements, the loads and the material law. However, these abstractions form their own independent classes. **FemStruct** does not need to know e.g. the type of an element, it just assembles them and puts them in a global frame. Its main responsibilities are topologic information about elements and the global assignment of degrees of freedom.
FemStruct gets its input from outside classes which control the whole project (c.f. section 3.9 "Project management").
The second abstraction with global level concern is the class **FemSolver**. It assembles the global equation system as required by the actual solver type, and solves it. It is the responsibility of the project control to choose and assign an adequate type of solver.

The abstraction which probably influences the quality of an FE framework design to the greatest extent is the one for a finite element (**FemElem**). Here the designer has much freedom and even

greater responsibility to separate levels of concern. Elements may be characterized by their geometric shape (bar, triangle, etc.), by their mechanical behavior (bar, beam, etc.), the field variables acting in them (displacements, stresses, water pressure, etc.), and the governing material law. In conventional programs often individual combinations of these characteristics form different element types. IMAGINE adopts another approach. This is indicated by the fact, that currently **FemElem** does not have any subclasses at all. The **FemElem** class itself is directly responsible just to provide geometric and topologic information. All other characteristics are covered by element-independent abstractions. If required, the corresponding objects may be linked dynamically to **FemElem**, i.e. it serves as a sort of container. **FemElem** just assembles the information from these objects, e.g. to form the material matrix, without being aware of their type. In this way **FemElem** is completely open for integrating future extensions, e.g. the introduction of a new type of analysis or field variable, or a new shape function.

As for the element also the abstraction for a material **FemMaterial** has no subclasses. This is achieved by extensive separation of levels of concern. Analogously to the element, **FemMaterial** serves as a container, but not for field variables and numerical objects, but for constitutive laws and their properties. I.e. constitutive laws are situated for **FemMaterial** at the same level of abstraction as field variables for **FemElem**. They may be linked to **FemMaterial** dynamically. And in fact in the actual implementation of IMAGINE they are derived from a common base class. If a material behavior is path-dependent gathering the actual data is delegated to the project control. Thanks to this design the introduction of a new material law should be possible without changing the underlying concept.

3.7 Geometric modeling

Although the FE kernel is the most demanding part from an algorithmic point of view, from the user's perspective creating the geometric model, meshing it and displaying the results are not less important. Conventional codes usually rely on a one-shot analysis, i.e. an FE mesh is created, an analysis is executed and the corresponding results are interpreted. However, in general the errors introduced with the discretization should be estimated (c.f. Kelly et al., 1983) and the mesh eventually (automatically) be refined until reaching the desired accuracy (c.f. Gago et al., 1983).
An efficient data structure for representing the mesh with its host of geometric, topologic and physical information is quite different from that of the data structure of a geometric model. Therefore, it was decided to separate the two items completely. A different solution, i.e. a unified treatment is presented by Kela & Peruchio (1988).

Thus the first independent step is to create a geometric model. The results of which in form of tables of solids, faces, edges and vertices may then be used by an automatic mesher as described below.
The most promising approach to create a geometric model which is valid in 2D as well as in 3D, is solid modeling. A solid model defines the geometric shape of a closed subset of the 3D space in a sufficient way, emphasizing completeness, integrity and geometric coverage or accuracy (Mäntylä, 1988). Three main representations of solid models are available:

- Decomposition models, where solids are decomposed into simple primitive objects (e.g. cubes) which are glued together. Decomposition models are seldom used and are therefore not further taken into consideration.
- Constructive models, where a model is constructed by combining (not only gluing) primitive solids (e.g. intersection of an infinite cylinder with two disks). The Constructive Solid

Geometry approach (CSG) uses bounded primitives instead of infinite ones. A prominent example of software relying on CSG was (up to version 12) AutoCAD of Autodesk Inc.
- Boundary models, where a solid is represented by its boundaries, i.e. faces, which again are represented by its boundaries, i.e. one-dimensional curves. The importance of this representation is underlined by the fact that AutoCAD is based on it starting from version 13 (AutoCAD user's guide, 1995).

It may be shown (Boender et al., 1994), that the FE mesh generation procedure requires a boundary representation for the derivation of an accurate mesh. The derivation of a boundary representation from a CSG model may potentially be possible, but it is expensive. In contrast by definition the boundary model provides this representation directly. Therefore, it was decided to rely on boundary models.

Boundary models have long not been widespread, but Mäntylä (1988) presented a standard text book, which could serve as a comprehensive guide for an implementation. His half-edge data structure could be a prime example for an implementation based on object-oriented design. Each solid object is made up of face-objects, which are defined by objects of vertices and edges. Each of these objects is able to respond to messages e.g. **glueSolid**, **sweepFace**, **getCoord**, **getStartingVertex** etc.
As part of IMAGINE a class system for a polyhedral solid modeler was implemented in C++ which may define solids of any complexity within the scope of boundary models. The so-called Euler operators may be applied, faces may be rotated and swept and solids may be glued together. At present, however, boolean operations (e.g. subtraction of two solids) are not yet implemented, and also the user interface is missing.
The advantage of an integrated solid modeler is that it may be tailored specifically to the needs of Geotechnics. However, its universal power may never compete with solid modelers written by dedicated software companies.
Therefore, additionally an interface has been implemented to allow importing the geometric model from third party solid modelers. The number of CAD programs based on boundary solid modelers which run under several operating systems, including MS-Windows, is still quite limited. Examples are:
- AutoCAD of Autodesk Inc. since v.13 [http://www.autodesk.com/].
- FEMAP of Enterprise Software Products Inc., Exton PA, U.S.A. [http://www.entsoft.com/].
- MegaCAD 3D of MegaTech Software GmbH, D-Berlin [http://www.megacad.com/].

A conversion program may be implemented which translates the output of such CAD programs to lists of solids, faces, edges and vertices which can be read in and interpreted by IMAGINE.

3.8 Postprocessing

Similar to the situation described above, the power of postprocessors produced with our limited resources cannot compete with tailored third party software for this purpose. It was decided to concentrate forces on engineering aspects, and use software from other companies for postprocessing. However, it was not easy to find a powerful program. Most graphics software is able to display curves and 3D-plots of corresponding sets of data. However, e.g. values at the excavation surface of a tunnel are interpolated with sophisticated algorithms and displayed accordingly also in the area of the excavation itself. This means that the graphics software must also take into account topological information in addition to the pure data. The only program found which runs on MS-Windows machines is Tecplot of Amtec Engineering, Bellevue WA, U.S.A. [http://www.amtec.com/].

A conversion program has been developed which can be called by a click of the mouse directly from within IMAGINE. It converts output data of IMAGINE to a format interpretable by Tecplot, and loads Tecplot with the corresponding data automatically.

3.9 Project management

In conventional programming, the FE kernel is usually considered to be the most important part of an FE system, whereas its management is condensed to a sequence of instructions specifying when and what to compute. Thereby it is often overlooked that the FE kernel takes over responsibilities of the management system, e.g. the definition of the computational tasks.

Following the object-oriented approach with its separation of concerns, the management of the projects and its resources should be completely separated from the concerns of the FE kernel system. In this way it may easily be seen that the project management has far more responsibilities than usually assumed. As a fact, it is at least as important as the FE kernel itself, which may be illustrated e.g. through its greater size in terms of lines of code.

Managing the project and its resources includes geometric modeling, defining the resources, defining the computational tasks, and dispatching them for execution. All these items refer principally to a higher level of abstraction, i.e. they do not refer to the level of discretized finite elements. E.g. a load may be defined for a geometric zone. Its assignment to individual finite elements is done later by the FE kernel before solving the system of equations. I.e. the project management includes all definitions of resources and their management, including the definition and dispatching of computational tasks, but excluding all definitions and manipulations at the level of the finite elements themselves. Only preparation of the mesh is also included here.

In somewhat greater detail the project management has four responsibilities:

- Project control at the uppermost level. This includes steering the user interface.
- Geometric modeling: definition of the project geometry in terms of a solid model. Conversion to data structures suitable for meshing. Actual meshing.
- Resources: definition of all resources, e.g. loads, material laws, geometric subregions.
- Analysis: definition of computational tasks, execution of the analysis.

The strict separation of the individual levels of concern facilitates inclusion of future extensions. E.g. computational tasks are treated like other resources. They are completely separated from the analysis. This may facilitate using artificial intelligence techniques for the definition of these tasks.

Thanks to OOP the project management is much less rigid than its conventional counterpart. OOP favors "non-anticipation" by its design. An object is a self-contained conceptual entity, on which all foreseen methods may be employed at any time. Before it exists it cannot be manipulated. Translated to the project management this means that the sequence how the responsibilities are fulfilled is of subordinate importance. If an object does not exist, it cannot be acted upon. E.g. assigning a distributed load to element nodes cannot be done before the mesh has been created. If a method needs more information to be executed, this will (if possible) automatically be created, and thanks to OOP mostly without any special provisions from the programmer's side.

3.10 User interface

It is considered that the user interface is not inherently a necessary part of a framework. However to prove the applicability of the framework for building real world applications and solving geotechnical engineering problems, a user interface for defining and solving examples seems to be indispensable.

The main emphasis of current programs when defining user interfaces is ease of use. However it often seems that not too much effort is invested in a clean and consistent design. The whole framework IMAGINE is strongly based on the OOP paradigm. Also the project management described in the previous section completely relies on this paradigm. The user interface is basically just a visualization of the project management. Therefore it is likely to employ also for the user interface an object centric approach.

According to section 2.4 OOP is characterized by data abstraction (classes), inheritance and polymorphism.
Applied to a user interface, data abstraction means that first project resources are represented by objects. This is automatically fulfilled due to the nature of the underlying system. But furthermore also graphical items, as forms, may be abstracted as classes.

Inheritance may be represented by e.g. hierarchies of forms. A user may for example like to assign some support attributes to a curve object. For this he opens a command form at its most generalized level, where the specialization (category) of the command may be chosen, for this case *Constraint Control*. In the next form he may choose a certain kind *of Constraint Control*, e.g. *Apply Constraints*, and so on.

Polymorphism is used by the user interface, e.g. for binding the command chosen above to the command object. However this kind of polymorphism is just used in the implementation, it is not directly visualizable by the user interface.

3.11 State of the Art

Recently, OOP has been applied to FEM by various authors. Although the specific interests have been different, the common basis has been to model more closely the concepts of interest.

In a first approach several authors discussed the advantages and applicability of OOP for the field of structural engineering. At the most general level Fenves (1989) presented a model of engineering information based on data objects that had a direct mapping to components in an engineering system. Already directed more towards FE, Miller (1988, 1989) discussed problems of persistence and concurrency, and developed a simple framework in LISP. A more sophisticated framework (implemented with the Common Lisp Object System) has been presented by Rehak (1986), Baugh and Rehak (1987 and 1989), and Rehak and Baugh (1988). The work of Rehak and Baugh may be considered as the definitive proof of the concept of OOP for an FE framework.
Forde (1989) converted the conventional Numerical Analysis Program (NAP) to an object-oriented counterpart (Object NAP) and compared them with each other. Object NAP built upon the MacApp Application Framework (Apple Computer, 1986) and was written based on a weak type system in Object Pascal. Forde emphasized the different control architecture of OOP compared with conventional paradigms: event driven compared to a rigid sequential algorithm. An event driven architecture is especially advantageous in connection with knowledge based expert systems, where heuristics are used to determine the next events to be dispatched.
Dubois (1992) implemented a FE program both in Smalltalk and in C++, and compared the advantages and disadvantages of these languages for this specific type of application.

All the above mentioned frameworks have more been developed as a proof of the concept, but less for use in engineering practice. Of the latter two groups may be distinguished: one group to be used by students and interested engineers, where the didactic aim is in the foreground, and the other group, which is envisaged to be extended by programmers to meet specific new requirements.
Yoon's (1990) "tutorial framework" certainly belongs to the first group. He emphasized the danger of misuse of sophisticated FE programs by less experienced analysts and postulated, that an analyst should be educated so that he could write an own simple FE program. Therefore, Yoon implemented an FE program in C++ intended for teaching FE programming and understanding FE behavior. Fan (1990) followed a different approach to avoid that the easier handling of FE applications is more and more entrusted to less experienced analysts with the danger of improper modeling and misinterpretations. To transfer aggregated experience Fan integrated knowledge-based expert system technology into an FE system.

Frameworks of the second group which aim to be extendable have been presented by Langtangen and Sims. Langtangen (1993) implemented a collection of C++ libraries named Diffpack for solving partial differential equations (PDE), where, in contrast to ordinary differential equations, the sought function u depends on several independent variables ($u = u(x1, x2, \ldots xn)$. Diffpack allows one to easily incorporate new solvers and preconditioners.
Sims (1994) developed an open and extensible FE development environment in Objective-C. The graphic user interface together with a new language enables the engineer to develop specifically tailored FE applications, without having to be an expert programmer and to know much about the OOP paradigm. The current environment concentrates mainly on enabling formulation of different finite elements. The environment represents a foundation with a great potential for

building future applications. However, in its present state with about 41'000 lines it is rather a proof of concept which requires major enhancements to be applicable as an FE building instrument (for comparison: IMAGINE has nearly four times as much lines of code).

A variety of contributions has been made which address special problems of FE programs, which advantageously may be solved relying on the object-oriented paradigm.
A special problem of any FE package is the proper solver itself. Over the last decades a variety of algorithms has been proposed, but only a few with regard to OOP. Yu (1994) discusses the solution procedure under this aspect for the Gauss elimination method and for iterative methods, which he found to be especially efficient with regard to both memory requirements and computational speed.
Another topic is computer aided design (CAD) and exploiting the power of solid modeling. Kela (1988) describes a hierarchical substructuring analysis technique that coupled with a solid modeling system permits algorithmic error evaluation and efficient localized reanalysis.
Abdalia and Yoon (1992) integrate finite element and graphics application programs to become parts of an integrated civil engineering system.

Summarizing it can be said that despite the above mentioned important work which has proved the potential of OOP, it is still not widely used in the scientific and engineering software community. Just coding in C++ does not mean exploiting the object-oriented paradigm and its advantages. Two facts may be the reason for this slow progress: firstly the great majority of existing code is still based on the procedural paradigm. I.e. programmers cannot avoid studying and working with procedural programs. Secondly, the underlying concepts of OOP are difficult to grasp and even more difficult to employ, especially for non informatics engineers, who usually are in charge of implementing geotechnical FE codes.

Up till now several frameworks have been presented which are more or less extendable. However, the extendibility is limited to a few specific directions, e.g. the introduction of new element types or solving strategies. Much less support is available for task control, creation of new material models or extending the analysis model. No object-oriented framework is available which is especially designed to cover the problems encountered in dealing with geotechnical engineering. IMAGINE tries to close these gaps.

4 Object-oriented design and implementation of the FE framework IMAGINE

4.1 Guidelines

Since OOP is still a relatively new concept, the understanding of how a *good design* may be characterized has varied substantially in the last years. Additionally, OOP is a paradigm, which is more powerful than any previous one (c.f. "Appendix 1: From procedural to object-oriented programming"), but is also much more comprehensive and difficult to apply. Therefore, personal interpretation and preference play an important role, even taking into account the many guidelines published on the subject (e.g. Riel, 1996).

As an illustration of this the following example may serve. Sometimes it may even not be obvious which class should be derived from the other. Is a beam an extension of a bar, where forces may also act outside the axis, or is a bar a special kind of beam where only forces in its axis are acting? Both interpretations may be found in literature, even from such respected authors as Miller (1989). The problem arises from the different derivation relationships as introduced above: specialization, extension or modification. IMAGINE tries to avoid this ambiguity by relying principally on specialization only. Extensions and modifications may often be regarded as an independent concept which should be modeled with their own independent classes.

Another subject of dispute is how far *capabilities of a class* should go. An often used guideline of OOP is that the whole knowledge of a class should be locally embedded. E.g. an element should also know how to plot and print itself. IMAGINE follows a different approach. Plotting is considered to be an independent concept which is modeled accordingly outside of any element or node class. Whereas the first model will be simpler for smaller projects, the second model with its extensive separation of concerns will be necessary for more sophisticated frameworks.

C++ is inherently based on strong *typing*, in contrast to e.g. Smalltalk. Weak type systems allow to identify the data type of an object, and are therefore well suited for object management. The NIH class library (Gorlen et al., 1990) proved that it is possible to simulate a weak type system also with C++. However, the overhead for providing a Smalltalk like environment is quite big. Therefore, as a rule, IMAGINE adheres to strong typing. Only where persistent objects are required weak typing is introduced by means of MFC's so-called runtime classes. Some more information about MFC and its runtime classes is provided in Appendix 3: The Document-View Concept of the MFC.

Besides such guidelines as mentioned above which belong to the "artistic" side of OOP, also some guidelines directed towards the "handcraft" side should be obeyed. A lucid programming style is an indispensable prerequisite for maintaining a large program. During the development of IMAGINE a set of rules has been established which is summarized in Appendix 4: Style guide.

4.2 Architecture of IMAGINE

When developing a framework for the FE domain, two issues will be of central importance: to design an architecture which is adaptable to future requirements, and a data organization which is easy to use, guarantees data integrity and consistency, and avoids redundancy. Without object-oriented programming, it is extremely difficult to satisfy these aims. But even when basing on OOP it is largely up to the design how far one goes to reach these aims. OOP employed in a narrow sense may just help to write conventional programs in a better style. At the other extreme, i.e. when OOP is exploited to its full extent, even a large program system may be developed which is still perfectly lucid and manageable. The price for this is a big expense in its basic design. IMAGINE's approach is more oriented towards the second way. About 80% of the effort has been invested in a comprehensive class design, and only about 20% in developing a simple application in the sense of a "proof of applicability".

The first design decision was to completely separate everything which concerns the FE method from the items which concern managing an analysis, starting from the input, executing an analysis and assembling the results. Accordingly the class architecture is based on two subsystems: one for the *project and resource management*, and the other for *FE modeling* (Fig. 4). Each subsystem includes several main abstractions (class hierarchies) which are used to model different concepts, each for its own domain of competence.

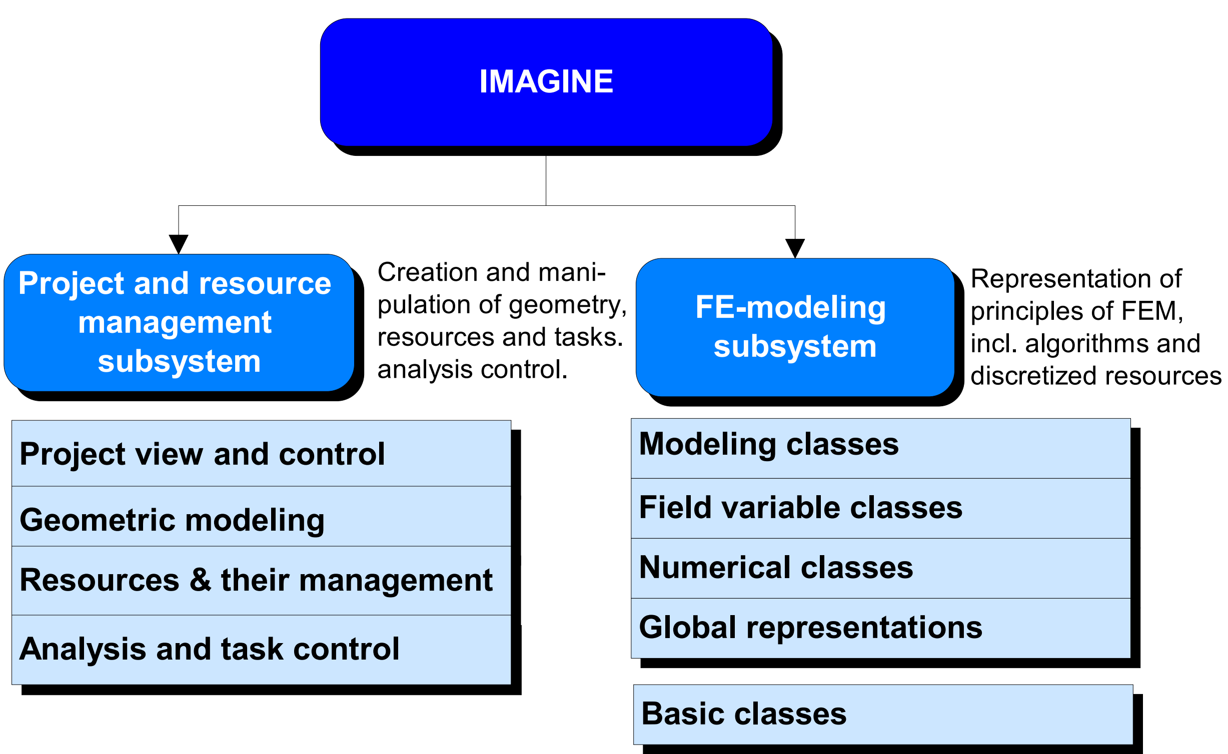


Fig. 4 General class architecture

The *FE modeling subsystem* includes the computational abstractions of the principles of the finite element method:

- modeling classes, e.g. FE types, nodes with information about geometry and element connectivity,
- field variable classes, e.g. stresses and strains, degrees of freedom,
- numerical classes, e.g. templates of shape functions,
- global representations, e.g. the global discretized FE system, the equation solvers, and
- basic classes, vectors and matrices, points, and coordinate systems.

The *FE modeling subsystem* provides the necessary classes or data types to build a comprehensive representation of the underlying FE domain. However, the creation and manipulation of the representation has to be done at another level. This level is often considered to be the concern of user interfaces in graphics environments, or of macros or command parsers in conventional batch programming. In contrast, following the object-oriented philosophy the decision which data or objects should be created should be delegated to the project control, and when to apply the loads to the task control. Both controls should be modeled as fundamental classes.

In IMAGINE this domain is realized in the *project and resource management subsystem*. This subsystem is considered to be equally important as the *FE modeling subsystem*. It includes

- the project view and control, which is responsible at the highest level for the views and the control of the project,
- the geometric modeling, which is the intermediary between the geometry as defined by the solid modeler and the one used by the *FE modeling* subsystem,
- the resources and their management, typically applied to zones or regions, and
- the analysis and task control, where the individual computing tasks are defined and the actual computation is executed.

4.3 Project and resource management subsystem

4.3.1 Project view and control

The top level class of the architecture is class **CFemProject**. **CFemProject** is the abstraction of a whole FE analysis project: it "knows" everything about the geometry of the project, it has a resource database to store and query mathematical or engineering data like loads, constraints and material properties; and it contains a set of tasks (e.g. *Apply Loads*) which can be used to execute a complex computation which may depend on dynamically changing boundary conditions, e.g. a mesh refinement based on accuracy criteria.

CFemProject class itself does not know anything about what kind of engineering project or physical system it represents, nor about the type of resources and tasks it contains. This is the responsibility of its derived specializations. Such specializations may be defined with regard to physical field concepts (e.g. stress analysis, seepage analysis, etc.), or according to the modes of these fields (plane deformation, plane stress, etc., c.f. Fig. 5). Furthermore, specializations could also be based purely on engineering concepts, such as a "Tunnel Stress Analysis Project". With this approach a high level interface may be provided which directly corresponds to e.g. a tunnel project and its construction procedure.

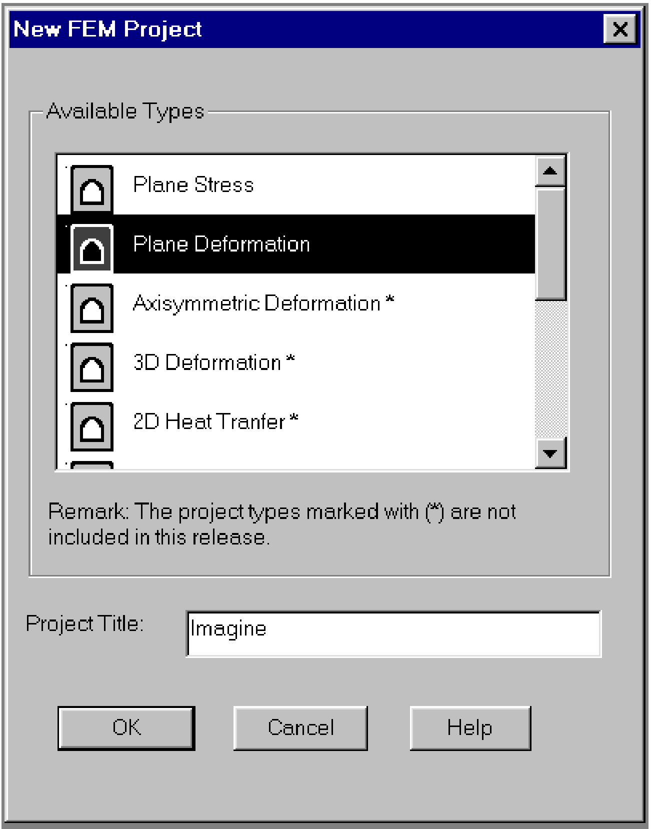


Fig. 5 Instantiation of an FE project

An important characteristic of a **CFemProject** object is that it keeps all member data of the project, i.e. the project itself, *persistent*. In an application, **CFemProject** object can be saved and opened. While **CFemProject** does not actually implement the details of saving and restoring, it orchestrates all other objects it contains to do the job thanks to the serialization mechanism of the MFC.

Once a new derived class of **CFemProject** is defined in the code, it becomes a project template and will automatically be listed as shown in Fig. 5. At any time during execution, there may be only one project object instantiated. However, one can always edit the current project, open a previously saved one or create a new one based on the template.

CFemProject abstracts the domain of the data of a project, together with its manipulations. This domain is completely separated from the view of the data. In this context, view comprehends not only organizing the actual display of the data, but also receiving and forwarding all user interactions which could change the display either directly or by changing the underlying data. The view concept of IMAGINE relies on the *Document-View Concept* of the MFC (c.f. "Appendix 3: The Document-View Concept of the MFC"). The basic classes participating in this concept may be seen from Fig. 6.

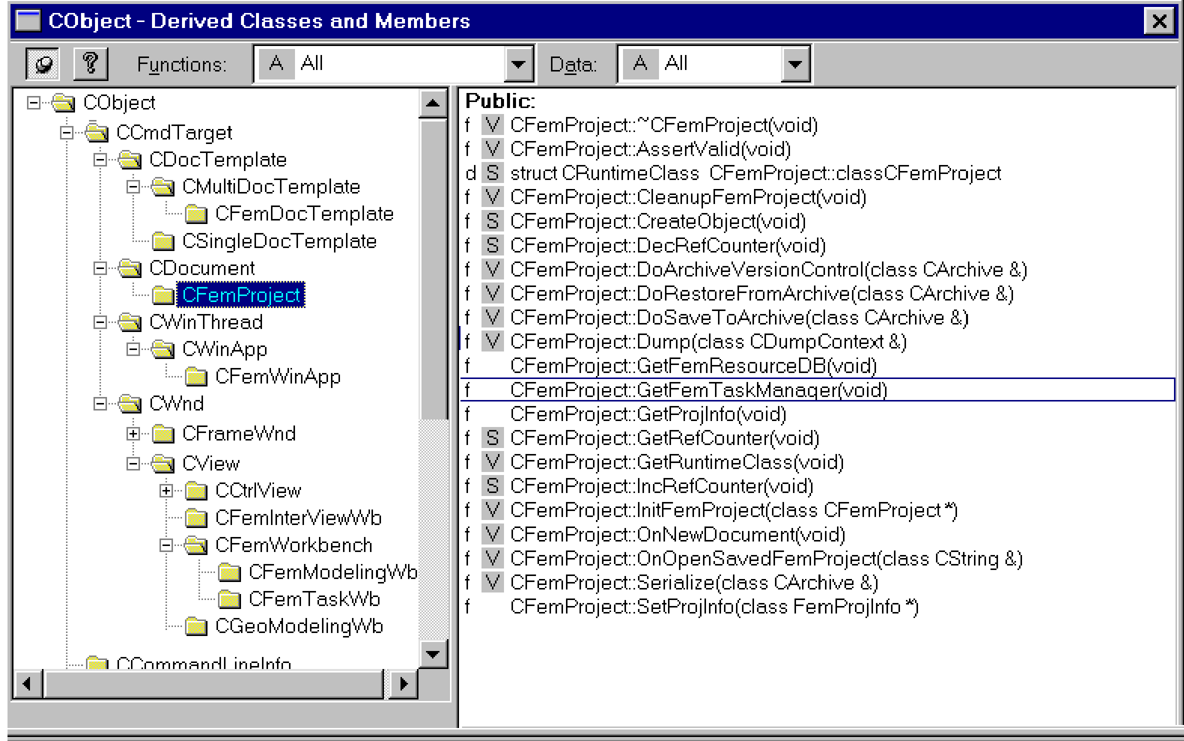


Fig. 6 Basic classes participating in the *Document-View Concept*

Due to its high level of abstraction, essentially **CFemProject** just represents the control center for a specific application. However, the actual organization and representation of data together with their management is the responsibility of the subsystems for *geometric modeling*, *resources and their management* and *analysis and task control*.

4.3.2 Geometric modeling

The geometric representation abstraction is introduced to separate the concerns of geometric definition, classification and representation of a project.

The geometric representation is modeled by two class hierarchies, **GeoDomain** and **GeoDomainRep**, as shown in Fig. 7. They are used to numerically represent project geometry. Although class **GeoDomain** appears more close to common concepts, as default, it does just provide two group of interfaces: one group for **CFemProject**, which will query the geometric properties when required, and the other group for **GeoDomainRep**, where the geometric data are stored and managed.

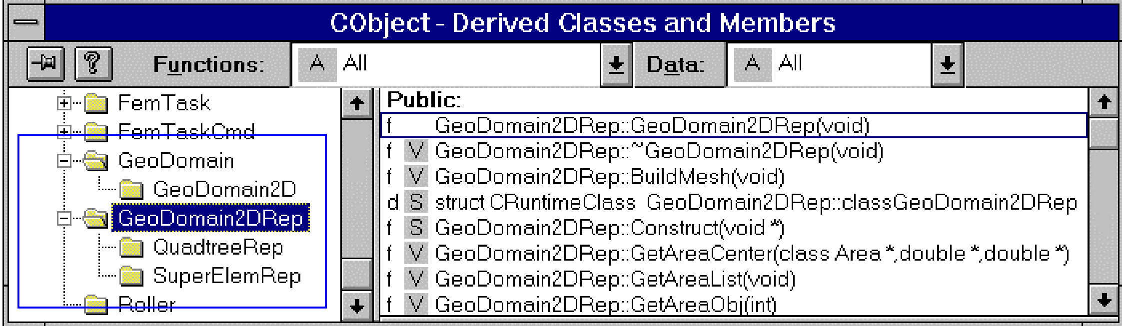


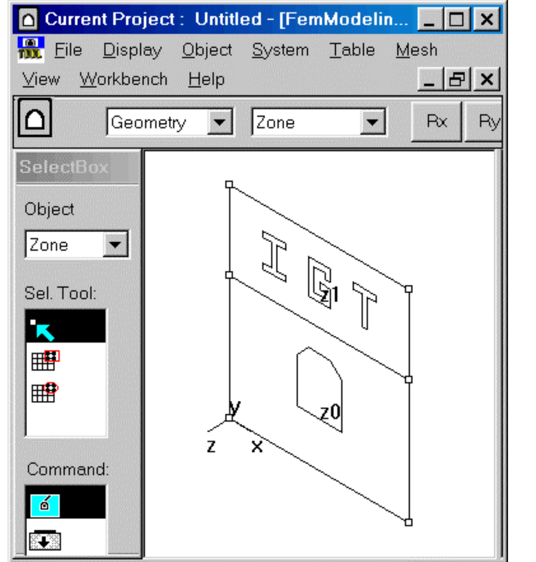
Fig. 7 Geometric modeling abstraction

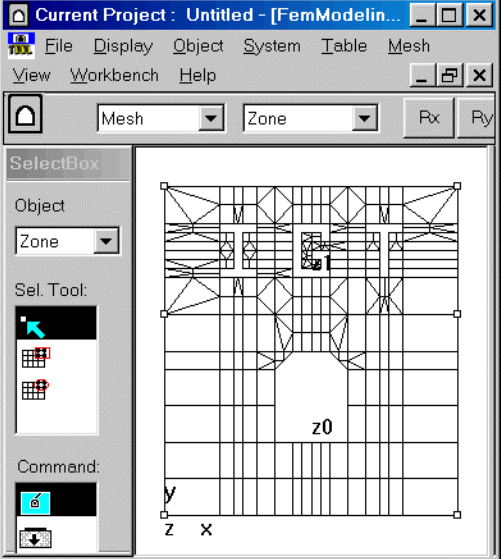
The actual geometry organization and representation is encapsulated within class **GeoDomainRep**. This is in fact a huge subsystem. It is one of the main topics in the CAD/CAE field. It has been abstracted so that it may be extended by means of derived classes with new emerging geometric representation models.

The most important competencies of **GeoDomainRep** are the capabilities of *querying*, *computing* and *spatial decomposition*. "Querying" refers to the capability of all geometric objects to be queried quickly on demand. "Computing" allows the determination of geometric quantities like volume, area, and center. The most demanding capability is the spatial decomposition. Here, spatial decomposition means the spatial subdivision into a regular mesh. This may also be referred as the process of automatic mesh generation.

To be as general as possible for both 2D as well as 3D problems, geometry is expressed as a solid model. A solid is a bounded, closed subset of the 3-dimensional space. Solids may be modeled by Boundary Models, Constructive Models or Decomposition Models. IMAGINE relies on the Boundary Model approach. For this a solid is represented by its boundaries (faces), the faces by their edges, and the edges by vertices. Boundary Models are typically created by sweeping 2-dimensionals faces, and by unifying, intersecting and subtracting individual solids. From the user's perspective the Boundary Model approach is especially suited for graphical constructions. From the programmers perspective boundary models are prime candidates for an object-oriented approach.

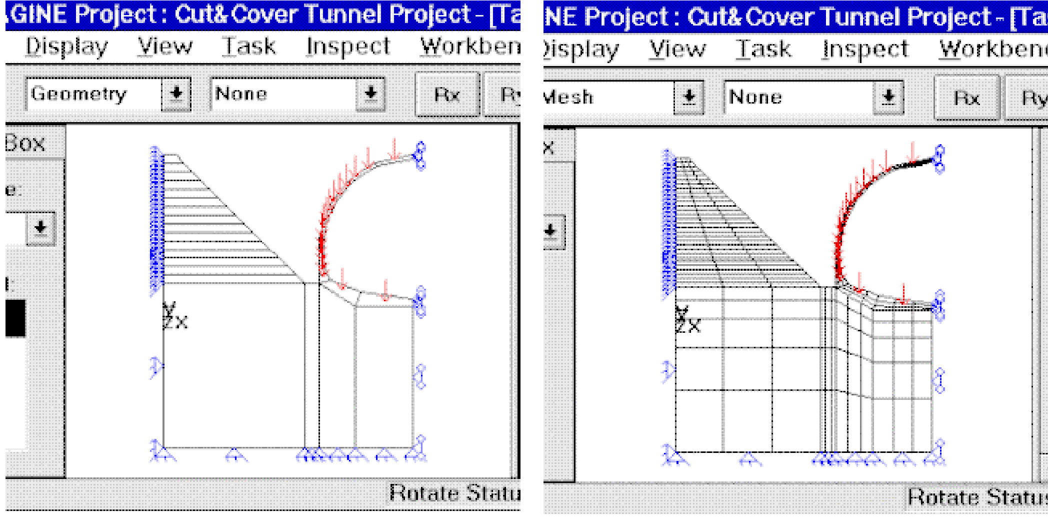
In the course of the IMAGINE project an independent solid modeler was developed which applies the theory of Mäntylä (1988) to OOP. This modeler could serve in the future to integrate in IMAGINE the possibility to quickly define the geometry based on predefined templates (e.g. a cut-and-cover tunnel). On the other hand, all 3rd party solid modelers can be used (e.g. AutoCAD, MegaCAD) which export their data as a face/edge/vertex structure.





a) Geometry of **QuadtreeRep** object

b) Mesh of **QuadtreeRep** object



c) Geometry of a **SuperElemRep** object

d) Mesh of a **SuperElemRep** object

Fig. 8 **QuadtreeRep** and **SuperElemRep** approaches

However, to our knowledge, up till now no algorithm for automatic FE mesh generation exists for the boundary model data structure. Therefore, although **GeoDomainRep** may read the geometry according to the Boundary Model approach, it is responsible to convert it to a form accessible for automatic mesh generation engines.

Currently two derived classes of **GeoDomainRep** for 2D domains have been developed which differ basically by their automatic mesh generation algorithms adopted: **QuadTreeRep** and **SuperElementRep**.

The **QuadtreeRep** model adopts a quadtree spatial subdivision algorithm according to Müller et al. (1991) and allows a fully automatic mesh generation, including local refinement and unrefinement, without creating elements with obtuse angles.

The disadvantage of this approach is that for the moment it could not be made universally applicable for all problems in geotechnical engineering. Mesh generation engines usually work very well in the domain for which they have been developed, e.g. for semiconductor modeling. However, the "specialty" in geotechnical engineering is that very slim structural components with high stress gradients (e.g. a tunnel lining) are in the immediate vicinity of huge components (e.g. the rock mass itself) with only minor changes in their field variables. Therefore, the automatic mesh algorithms tested led to either too coarse a mesh for the lining, or to too many elements for the surrounding rock.

Therefore, **SuperElemRep** has been added which relies on user specified superelements as input data. These may be defined in a way to avoid the problems mentioned above. The user may then instruct IMAGINE to subdivide these superelements, leading to a very regular mesh fully controlled by the user. The drawback is that the initial geometry must be input in the form of superelements. Fig. 8 illustrates the applications of these two classes.

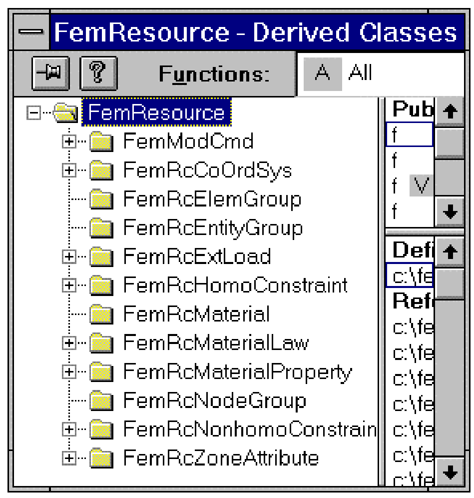
Some practical consequences for the two representations will be discussed in 6.3 "Solid model versus superelements".

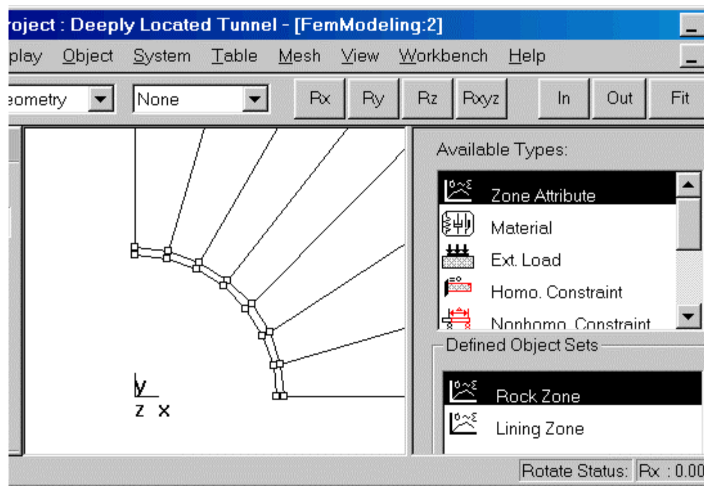
4.3.3 Project resources and their management

An FE run needs a variety of resources to completely specify a specific application problem. These may include material properties, loads, etc. Ultimately they must be known at the discretized finite element level. This aspect will be discussed in the context of the *FE modeling subsystem*.
Here, in the context of the *project and resource management subsystem*, these resources are treated at a higher level. E.g. a zone may be defined where certain characteristics apply. This zone is completely independent of the FE mesh, which at this abstraction level is not known.
These resources will be called "project resources". The project resource objects are responsible for creating and manipulating their "discrete" counterparts after the FE mesh has been generated.

Project resources are modeled by IMAGINE in the **FemResource** class hierarchy (Fig. 9), and include:

- **zone attribute resource**: defines the type of a zone and its associated material resources. The material resources themselves will be abstracted as a material resource class. The possible zone types may be structured according to the project specialization. E.g. a tunnel project may have zone resources designated as *Rock Zone*, *Lining Zone* and *Joint Zone*. Although several zones could share the same material object, their mechanical abstraction could be different, e.g. the element types and hence the element stress-strain matrix could be different. As default, a zone attribute resource will be defined for an entire solid or superelement, depending on the geometric modeling (**GeoDomainRep)** of the project.
- **material resource**: a material resource is a composite resource: it contains material property resources and material law resources. The admissible material property types and material law types for a project are compiled according to its host zone types. A material resource object can be referenced by several zone attribute resource objects.

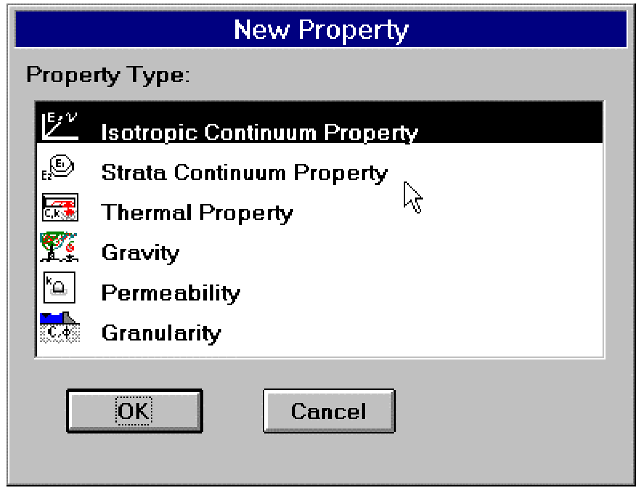


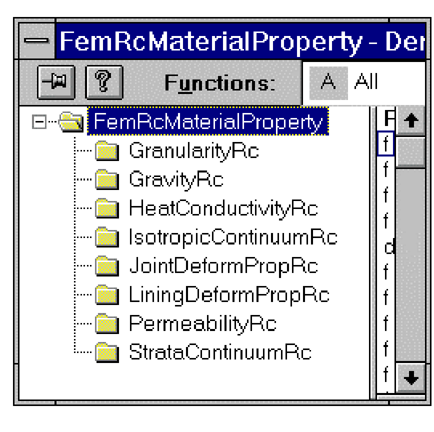


a) Architectural resource classes b) Examples: specifications of project resources

Fig. 9 Resource class hierarchy

- **material property resource**: used to represent any physical material property. The material property may be an individual value like an elastic modulus, a cohesion, or a permeability, or a set of properties. Some useful material property resources have been predefined including **IsotropicContinuumProperty**, **StrataContinuumProperty**, **HeatConductivity**, **Permeability**, **Granularity**, etc. Not all defined material properties will be used for a specific project. The relevant properties depend on the chosen project specialization and active zone types. Fig. 10 shows the visible material property types in a generic plane deformation project.
  A material property resource object is one component of a material resource object.





a) Property dialog of a tunnel project b) Property resource hierarchy

Fig. 10 Material property resources

- **material law resource**: used to model constitutive laws of a material. The programmer is completely free to place here any material model at the user's disposal.
  When and how the material laws will be used during a computation is considered to be the concern of the project view and control (c.f. **FemTask** in section 4.3.4 "Analysis and task control").
- **load resource**: here the term "load" stands for a broader concept. E.g. for a deformation analysis, it stands for forces.
  Subclasses of load resource should be derived to meet the needs of the project specialization and the geometric model employed. Examples of loads specific to rock engineering projects are **DeadZoneLoad**, and **ExcavationEquivalentLoad**. Examples of loads based on the geometric model are **ConcentratedForce**, **DistributedForce** or **BodyForce**.
- **homogeneous constraint resource**: the specification of the essential boundary condition concept of partial differential equations is abstracted as a constraint resource. The guidelines for derivations are similar to those of the load resource. Constraint resource objects can be introduced at vertices, along edges or on faces. An example of a homogeneous constraint is fixed support.
- **heterogeneous constraint resource**: the heterogeneous counterpart of homogeneous constraint resource. An example of a heterogeneous constraint is a vertex with prescribed displacements.
- **coordinate system resource**: a mathematical concept. It is universally useable regardless of the project type. Examples are **RectCoordSystem**, **PolarCoordSystem**, and **Cylinder-CoordSystem**. Once a coordinate system is created, it can be used by other resource objects.

These resource classes are called architectural classes since more specific classes can be defined for a specific type of project.
Already now, some more resource classes have been defined. E.g. a node group resource and an element group resource: they are used to group nodes and elements in terms of geometric entities.

A resource objects manager has been developed. It controls resource objects according to their classification but does not know anything about the exact subclassing system.
Resource objects are stored and managed by a resource database. This is a simple object database rather than a relational database, since objects are in the center of interest but not tables and records. Each project contains just one resource database.
Because all resource classes have the common ancestor class **FemResource** it is possible to derive more resource classes if needed, without requiring any additional steps. The reason is that from a management point of view the resource database is responsible for the **FemResource** object only, but not directly for its derivations or any implementation details.
A set of common interfaces has been defined to cover the communication needs between the resource classes and the resource object manager, and between the resource object manager and the host project object.

The class hierarchies for the geometric modeling domain and the resource domain represent a powerful abstraction and contribute to a welcome separation of concerns for the whole project.
The geometry and all resources of the project may be defined completely independently of the FE mesh, and thus provide e.g. a solid foundation for a fully automatic adaptive analysis even with complex geometric profile and boundary conditions.

4.3.4 *Analysis and task control*

Conventionally an FE analysis has been split into three parts. In the pre-processing phase all input data, i.e. geometry and other resources, are assembled. The actual computation solves the problem described by the input data. And the post-processor analyzes and displays the results.
While this is a natural division according to the working sequence, there is one more part which is less apparent but usually included automatically during the program design: the so-called driver part, which controls the flow of the computation.
The simplest driver program just calls a set of functions in a predefined order, such as applying constraints, applying loads, assembling the stiffness matrix and solving the equation system. In order to offer users the possibility to control the execution flow, many FE packages, e.g. RHEO-STAUB (Fritz, 1983), embed a macro-style command language. With this users may establish a kind of flowchart to simulate a complex engineering process.

IMAGINE regards the analysis and task control as an important part of *the project and management subsystem*. It is therefore abstracted into its own class hierarchy. At the uppermost level reside the classes **FemAnalysis**, **FemTask** and **FemTaskCmd**. They are differentiated according to their level of abstraction: **FemAnalysis** controls an analysis at the engineering level, **FemTask** contains the individual tasks which can be executed by **FemAnalysis**, and **FemTaskCmd** contains the actual commands how to execute the task.

FemAnalysis has the role of a control center. It sends messages to initialize and record the system state at its various stages, it communicates with other key components of the project like **FemStruct**, **FemSolver** and **ResourceManager**. The principal responsibility of **FemAnalysis** is to fetch the required **FemTask** objects and to dispatch them Fig. 11.

The name **FemAnalysis** was chosen so that its subclasses might be derived and named after the classification of conventional analysis, such as **ElasticAnalysis**, **ElastoplasticAnalysis**, **TunnelSeepageAnalysis**, etc. Each new subclass of **FemAnalysis** signifies a new analysis type, something which would probably lead to a new program under conventional conditions.
These subclasses are effectively responsible for manipulating the system state, because it depends on the analytic features considered. For linear problems, a snapshot of the current system state suffices, for non-linear problems with path dependence, probably the system states have to be stored for initial, incremental and final conditions.

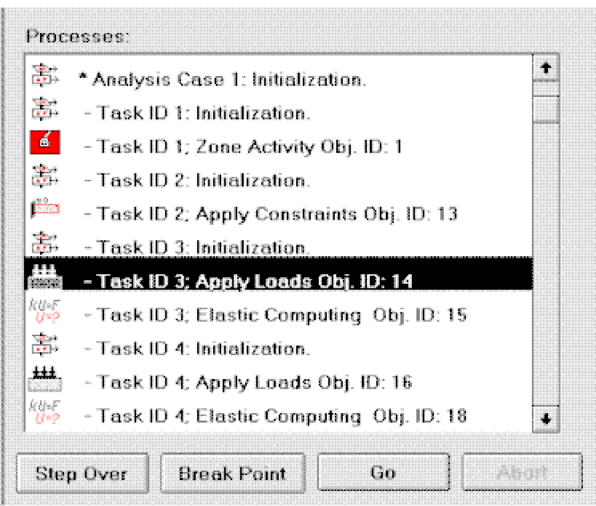
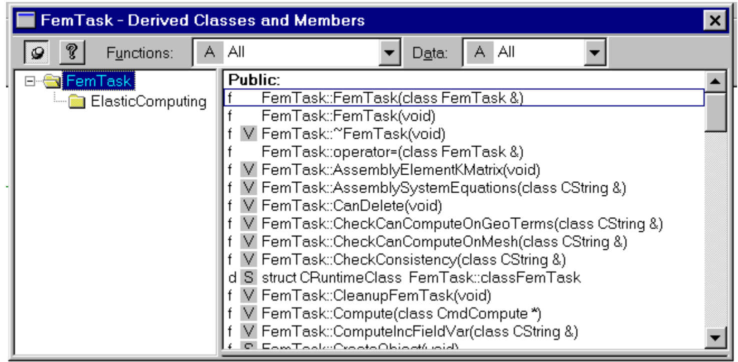
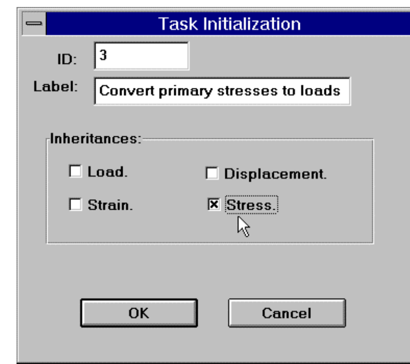


Fig. 11 Example of an analysis flow

FemTask contains the individual tasks which may be executed by **FemAnalysis.** The individual **FemTask** objects are part of **FemAnalysis** and are therefore modeled in their own class hierarchy (Fig. 12).



a) **FemTask** class hierarchy



b) Example of an Initialization Task

Fig. 12 **FemTask** abstraction

The key responsibilities of class **FemTask** are:

- to provide a set of common task data types that may be shared by different subclasses of **FemAnalysis**. E.g. an "elastic computing task" may be used by all deformation analysis classes.
- to combine a set of control events reflecting the underlying engineering background. This is based on the fact that often several numerical modeling steps are needed to model a single engineering step. It would therefore be advisable to combine such numerical modeling events in an autonomous analytic task. An example of such a task for an analysis of a cut-and-cover tunnel may be identified as "**NextLayerTask**" which may contain control steps like flush the previous load, determine the interface nodal loads due to the weight of the soil layer, compute, and update.
- to provide services for initialization and termination which may be needed for a task. An example is the "Inherit" service shown in Fig. 13, where an " initialization " dialog is used to prepare the initial state of a computing task.

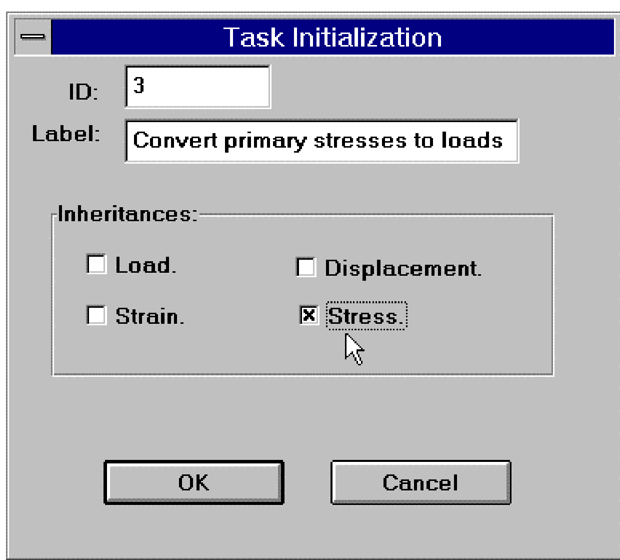


Fig. 13 Example of a *Task Initialization*

FemTaskCmd contains the actual commands or events which may be used by **FemTask** to fulfill its duty. One may develop and add as many events as necessary to support **FemTask** and **FemAnalysis** through subclasses. A default set of **FemTaskCmd** subclasses has been abstracted (c.f. Fig. 14) including:

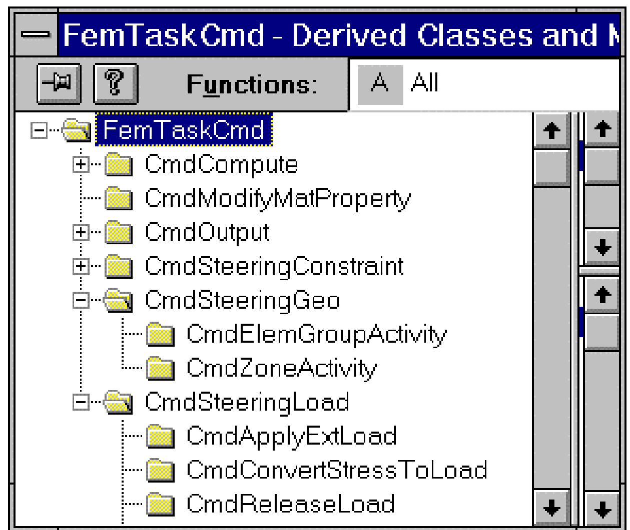


Fig. 14 Analysis-Task command classes

- geometric control commands: to activate and inactivate geometric regions or element groups.
- load control commands: to apply and release loads.
- constraint control commands: to apply and release constraints.
- material property reset: to modify material properties.
- computing commands: to specify a material law, a computing type and update options.
- output commands: to output desired results at a macroscopic level.

In IMAGINE **FemTaskCmd** is normally not assumed to directly create **FemResource** objects as discussed in previous sections. Instead **FemTaskCmd** object uses the appropriate **FemResource** objects in the resource database of the project. It sends them a message through the virtual

function "Execute" which in turn will call a virtual function, in case of **CmdSteeringLoad**, "Apply" or "Release" to modify a **FemStruct** object. One of the exceptions of this rule is **CmdCompute**, for which no corresponding computing resource concept exists. In this case the virtual function "Execute" of **CmdCompute** simply makes a callback to the virtual function "Compute" of the host **FemTask** object to execute the task.

4.4 *FE modeling subsystem*

4.4.1 Overview

The finite element method is a numerical tool with nearly unlimited power. While the general principles of FEM remain the same, the actual solution approaches may greatly differ from one engineering domain to another. It is practically impossible to enumerate them.
When designing IMAGINE it was tried to satisfy the two contradictory requirements: on the one hand, to provide as much power as possible for the application domain envisaged, and on the other hand to make the design as general as possible. IMAGINE is clearly positioned to fulfill the requirements within the domain of Geotechnics only. Its generality goes as far as necessary to be extendable for future requirements within this domain, but not further, to avoid unnecessary overheads.

The *FE modeling subsystem* is the second leg of the IMAGINE framework. It is responsible for the abstractions of the general concepts of FEM. These mainly include the general principles, the data representations, and the geometric and topologic concerns of the discretization. Special efforts have been made to cover future extension requirements. Examples of this may be extensions to include complex material models (c.f. Fritz, 1983), structural complexities (joints, lining), and field coupling (e.g. seepage-deformation), etc.

The *FE modeling subsystem* should not be understood just as a data structure as it would be in conventional approaches, nor as a black box of invariant components of IMAGINE. It is an integrated part of the whole framework. Its usefulness to develop subclasses of **CFemProject**, **FemResource**, **FemAnalysis** and **FemTask** all depends on the availability, capability and extendibility of this subsystem.

The *FE modeling subsystem* defines a set of generic architectural classes. Each architectural class abstracts a specific part of FEM. The fundamental problems of the transitions between global and local formulations specific to FEM are also dealt with at this level.
A simple FE application could be built just with the generic architectural classes. For more advanced applications subclasses of the generic architectural classes may be derived which make available required extensions. However, since most of the fundamental concerns, such as element analysis, local-global indexing, loading, associations between field variables, and storage management, etc., are covered as defaults by the generic classes, when developing an application one may concentrate on those features only which are relevant for the specific application.

4.4.2 Modeling classes and field variable classes

4.4.2.1 Overview

The physical side of FEM is governed by differential equations which are based on two fundamental elements: the definition domain (e.g. finite elements, supports), and the physical field variables which act in this domain. Consequently, the numerical model for the physical engineering problem, from an object point of view, may be composed of two groups of abstractions: *modeling classes* and analytic or *field variable classes*.

When applying FEM to solve PDEs, the geometry domain is discretized into a mesh. An equation system is built for a set of ordered field variables at the mesh points and solved simultaneously. Thus basically the *modeling classes* serve for building the system of equations, the results of it being placed in the *field variable classes*.

For a continuum, the *modeling classes* mainly refer to the classes which are necessary for the discretized representation of field variables, and classes which are used to interpolate field variables. In terms of FEM, these may include the mesh, elements, nodes, shape functions and interpolation functions, etc. Conceptually they are related to the interpolation theory and the spatial discretization principle, which are common to all physical application types. In an object-oriented design they form the highest abstraction level of an FE application.

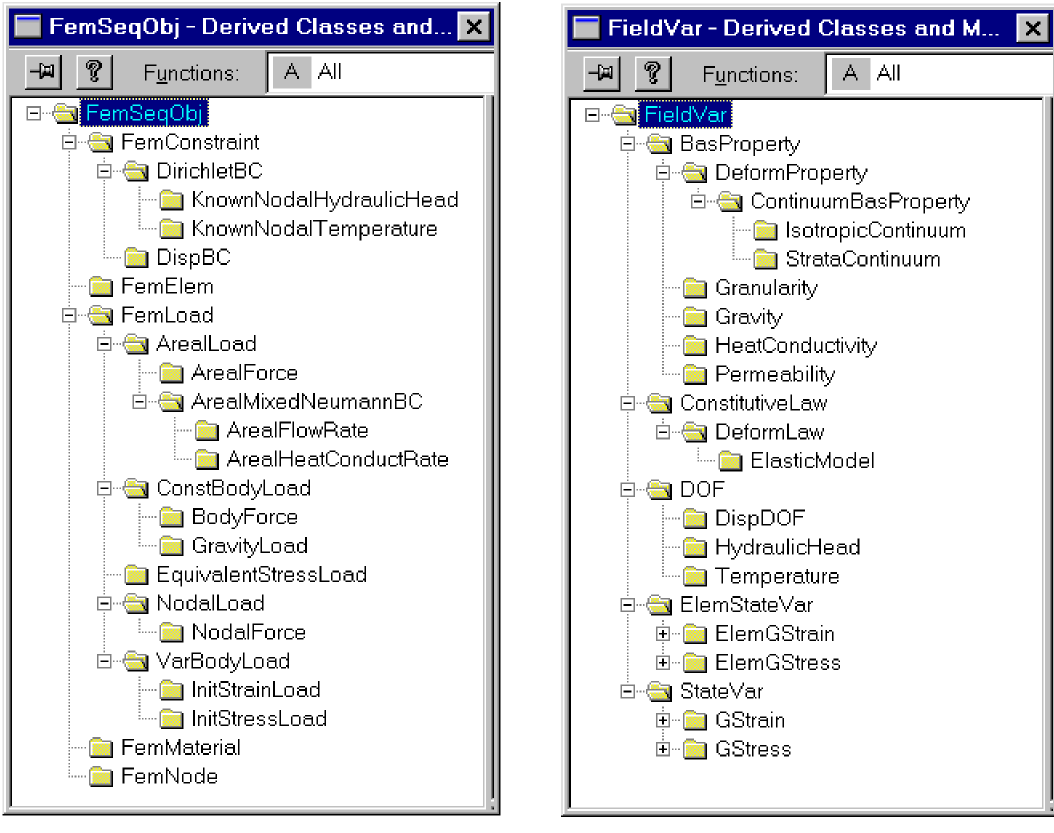
Usually an FE modeling system is implemented specifically for a well-defined physical field, such as a seepage problem or a deformation problem, where the physical background of the modeling concept and the corresponding field variables are clearly related and simple. They may be combined together to form so-called element formulas. The "Degree of Freedom" (**DOF)** class, for example, may naturally refer to the primary field variables of the underlying physical field, such as nodal displacements, without any ambiguity. The secondary field variables (e.g. stresses or strains), which are normally locally computable through interpolation of primary field variables, may be defined on demand and computed using the values of **DOF** without the need of further interpreting their type.

However, it would be a great advantage if an FE framework could offer the possibility to develop applications for different physical engineering problems. Such a feature would especially be useful in the field of geotechnical engineering. This can be verified immediately by viewing the list of demanding research topics in geotechnical engineering: stress analysis problems, groundwater flow problems, swelling problems and convection problems, which require taking into account the coupling of deformational, hydraulic and thermodynamic problems.

The design of an FE framework with configurable field variable types requires a complete review of the original theory of FEM. An immediate consequence is that the element formulas are now no longer constant even if the element shape and interpolation functions remain the same, since the element formulas are derived from a given field variable type. This may suggest deriving element types for the individual field variables or combinations of them. Each subclass of the generic element class would be defined specifically for a certain field type, such as a Laplace Element, a Deformation Element, etc., just similar to the widely used structural elements, like truss and beam elements. Since element formulas are just one of the concepts which are related to field variables, other class hierarchies would have to be defined in a similar manner, e.g. for

material laws, **DOF**s, etc. This would lead to a rather complicated class tree, which would be difficult to maintain. Additionally, it would be opposed to the object-oriented principle of localization of concerns: a *modeling class*, e.g. a finite element, should be separable from the physical field acting within it.

IMAGINE pursues a different course. It relies on two independent abstractions (Fig. 15), **FemSeqObj** is the root of the class tree which contains all modeling concepts, and **FieldVar** contains all types of field variables.



a) *Modeling classes* b) *Field Variable classes*

Fig. 15 *Modeling* classes and *field variable* classes

The most important *modeling classes* of **FemSeqObj** are **FemElem**, **FemNode**, **FemMaterial**, **FemLoad** and **FemConstraint.** The responsibilities of the *modeling classes* are further split into two levels: the connectivity part and the analytical part. In IMAGINE, the connectivity part is considered to be the "bones" of the FE modeling concept, while the analytical part is viewed as the "meat". At the architectural level, the *modeling classes* are mainly used to cover the connectivity concerns, the connections between bones, so that a generic frame can be built up. This is the reason for calling them "*modeling classes*". However, the analytical concerns of the *modeling classes* require both connectivity components and physical field variable components. The role of the base class **FemSeqObj** is to establish the connection via an ID between modeling components and their assembled structure of the whole FE system, which is abstracted in class **FemStruct** and will be discussed below. All subclasses derived from **FemSeqObj** inherit this capability.

The physical field variable components in IMAGINE are modeled as a set of *field variable architectural classes* with the following main components: **DOF**, **StateVar**, **ElemStateVar**, **BasProperty** and **ConstitutiveLaw**. Again, at this level, each of them only addresses the generic concept it represents. Subclasses may be developed to model effective components. All the *field variable classes* are derived from the base class **FieldVar.** One important role of **FieldVar** is to cover the association requirements of its subclasses. The need to model associations of field variables is less apparent if there is only one type of field variables. For example, if the framework is limited to simple elastic deformation, then **DOF** must be displacement, **StateVar** must be **Stress** and **Strain,** and **MaterialProperty** probably holds two values, the elastic modulus and Poisson's ratio. However, the association concept becomes important when **DOF**, **StateVar**, and **BasProperty** each abstracts a hierarchy.
In IMAGINE all objects of type **FieldVar** are given an ID attribute which gives information on the type of the field variable, and a list of IDs which gives information on associated field variable types. A field variable type ID is not a class ID. It is based on the classification of physical field types and field variable types. It is not a unique ID to identify a class type, but rather a unique key to identify the field variable type. The type ID of a class may serve to make some advanced features such as object persistence possible. The field variable type ID, however, provides a way to ensure that the manipulations of field variable objects are physically meaningful so that, for example, a strain object could only be computed from a displacement object, but from no other kind of field variable.

The field variable type IDs are based on the classifications or computational abstractions of physical field variables. Currently, seven entries for physical field variables are defined which are the most fundamental physical field variables from a computational point of view. Each entry represents a type of field variable. The field variable types are

- **FemFieldVarID** (physical field type, e.g. deformation problem),
- **FemNodeDOFID** (DOF type, e.g. displacement),
- **FemElemVarID** (state variable type for **FemElem**, e.g. **ElemGStress**),
- **FemStateVarID** (state variable type, e.g. **GStress**),
- **FemMaterialPropertyID** (fundamental material property type, e.g. **DeformProperty**),
- **FemMaterialLawID** (material law type, e.g. **DeformLaw**),
- **FemFieldCharacterID** (character of physical field type, e.g. **PlaneStrainMode**).

Every subclass of **FieldVar** will either inherit or be assigned a field variable type ID in order to be identified by its associated **FieldVar** classes. In addition, every subclass of **FieldVar** will either inherit or be assigned a set of associated field variable type IDs in order to access the objects of its associated **FieldVar** classes. Users of the framework can decide on and provide these IDs if a new set of field variables is introduced.

4.4.2.2 Element concept

The procedure to build a discretized FE representation of an engineering problem may be viewed from two perspectives: from the global or structural perspective, and the local perspective at element level. Examples of global level concern are the ordering of DOFs and the assembly of the system of equations. Examples of element level concern include information about element geometry and topology, and local mathematical and physical characteristics analysis.
The treatment at the element level is also called element analysis. Mathematically, the purpose of element analysis is to provide a set of formulas, the so-called element formulas. Element formulas differ from element-to-element, depending on the element's geometric shape, the interpolation functions, and the field variables of concern. Often a specific element configuration is referred as element type, such as truss element or beam element, which are named after their mechanical behavior, or triangle element, which is named after its geometric shape. Numerically, following a conventional approach, often a set of separated routines must be developed to handle the calculations of a specific element type at different stages.

On a first look, the introduction of an element data type (or class) when using OOP is expected to be a straightforward matter. However, on a second look it is recognized, that the design of such an abstraction is not obvious and could lead to a bunch of different approaches. At a first glance, it appears that element data types could be constructed according to the "element type" concept mentioned above. And effectively this approach could be used with certain element types like a truss, beams, or even simple shells. However, difficulties would appear integrating further extensions or configuration changes, such as general material models or new shapes, due to the lack of abstraction and separation of concern. Such an approach requires that for any possible combination of shape, material and field variable type, a new element data type has to be derived and many common operations like shape function derivatives have to be duplicated. This is obviously not the way to fulfill the promises of OOP techniques.

As a matter of fact, the responsibilities at the element level rely on a composite concept. It is a duty of a correct design to separate as far as possible the concepts that a generic element type is composed of. IMAGINE takes into account the following independent concepts: connectivity, geometric shape and shape functions, numerical integration, element field variables, material response, and coordinate system.

The base class of the element hierarchy is **FemElem** (Fig. 15a), which is derived from **FemSeqObj**. **FemElem** is an abstraction of a generic element. It is configurable in terms of **CoOrdSys**, **FemShape**, **FemMaterial**, **ElemStateVar**, etc. The primary responsibility of **FemElem** at this level is to provide coordinates and connectivity information through its node list to the outside. This includes also the geometric subdivision of an element.
Other capabilities of **FemElem** may be considered as open issues. The objects representing these capabilities will be created externally and bound to **FemElem** dynamically. Several **Elem-StateVar** objects representing different field variable types are allowed to be linked.

Additionally, the basic interface between the local element level and the global structural level is defined in **FemElem** at an abstracted level. It is a set of mostly virtual functions which get their content from member objects.
As default, **FemElem** assembles the information returned from its member objects, such as the interpolation scheme, geometric derivative matrix **B** and material matrix **D** to form inherent

element properties, such as element stiffness matrix and element nodal force vector, using standard element analysis formulas. At this level, **FemElem** does not know which "element type" it is. If required, subclasses may be derived to form "strong typed" element data types, which are less flexible, such as **JointElement** or **LiningElement**. Since many common capabilities are covered by higher level classes, these subclasses may concentrate on "what to do" rather then "how to do it".

Other capabilities of **FemElem**, e.g. how numerical integration is done, will be mentioned under the topic "Numerical Classes".

Point state variables versus element state variables:
As mentioned above, in IMAGINE field variables are abstracted in the class hierarchy **FieldVar**. The primary field variables are captured with **DOF** class hierarchy which will be discussed later, the secondary field variables, such as stress, strain, moment, rotation, heat and flow rate and gradient, are abstracted as subclasses of the two class hierarchies **StateVar** and **ElemStateVar**, as shown in Fig. 16.

StateVar is the abstraction of a secondary field variable, such as stress or strain. It is defined at a geometric point. It is mainly used for various mathematical operations related to the state variables themselves, but not related to the element concept.

For each **StateVar** subclass, there is a corresponding **ElemStateVar** subclass. **ElemStateVar** and its subclasses are the enhancements of their counterparts in terms of elements. The enhancements are considered to be necessary, based on the following considerations: firstly, element is the basic unit from the structural point of view. The integration points are considered to be the internal affairs of the elements only. It is therefore more logical to store and access the state of elements in terms of element values rather than in terms of point values. Secondly, with this approach the high level modeling class **FemElem** is released from managing the **StateVar** hierarchy.

Both **StateVar** and **ElemStateVar** are derived from **FieldVar** and must therefore be able to be identified through unique field variable IDs.

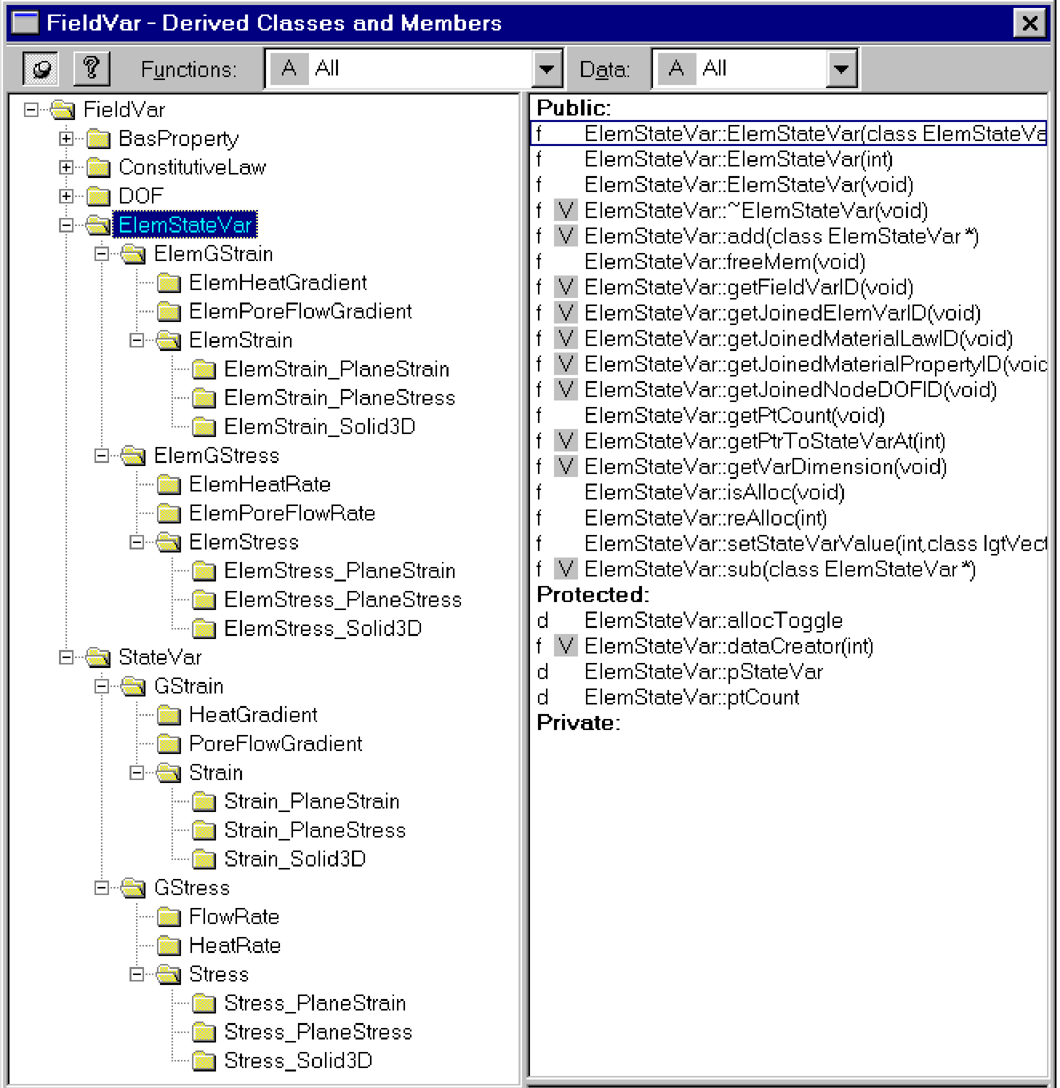


Fig. 16 Derived state variables

The subclasses of **ElemStateVar,** e.g. **ElemGStress** or **ElemGStrain**, carry a "G" in their names which stands for "generic". I.e. subclasses must be defined to allow instantiation. An important responsibility of the subclasses derived from **ElemGStrain** is to provide the **B** matrix which yields a " strain" from a "displacement" by interpolation over an element. This **B** matrix is used for the element analysis, e.g. for the calculation of the element stiffness matrix, or the calculation of "strain" from "displacement". All the subclasses of **ElemStateVar** are linked to appropriate **DOF** types and material properties through so-called association keys.

The class **FemElem** is designed to keep a list of **ElemGStress** objects and a list of **ElemGStrain** objects in order to allow handling of coupled problems.

4.4.2.3 Node and degrees of freedom (DOF) concept

The class **FemNode** (c.f. Fig. 15a) is used to model the node concept of a discretized finite element system. Similarly to **FemElem,** due to its extensive separation of concerns, it has currently no subclasses. It derives its power from a multitude of aggregate objects and member functions.
As default, the properties of a **FemNode** include: coordinates, a list of **DOF** objects, connectivity information, the values of primary nodal field variables, and the values of generic nodal loads.

The location of **FemNode** is represented by an object of **IgtPoint**. The connectivity property refers to the information regarding which elements are connected to the node. The values of "generic" primary field variables and loads are represented by a vector. The vectors are subdivided and arranged by **DOF** objects.

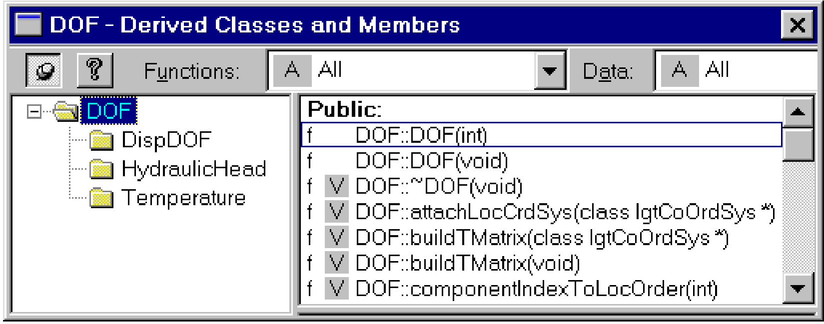


Fig. 17 **DOF** class hierarchy

The concept of the degrees of freedom at a node of a discretized finite element system is intimately related to the node concept. The **DOF** concept as introduced by IMAGINE (Fig. 17) should not be interpreted as the "number of degrees of freedom". **DOF** and its subclasses contain information about how many unknowns associated with a certain type of field variable apply in a **FemNode**, the state of these unknowns (free or constrained) and their indices in the discretized FE system. A local coordinate system will be provided wherever it is necessary since in practice the **DOF** objects sometimes may only be defined relative to a local coordinate system (e.g. for constraints applied at an inclined support).
Encapsulating DOF in a separate class allows hiding implementation details and changing their type and properties dynamically. As mentioned above the **DOF** class hierarchy contains the primary field variables (e.g. displacements), whereas the secondary field variables (e.g. strain) are contained in the two class hierarchies **StateVar** and **ElemStateVar**.

The class hierarchy **DOF** is derived from **FieldVar**, i.e. it also falls into the model of ID key and associated ID keys which should be provided by the **DOF** subclasses.
Each class of **DOF** class type returns an ID which is defined in the **FemNodeDOFID** field of class **FieldVarID**. Currently, three physical field types are considered: deformation, heat transfer and groundwater flow. Accordingly the DOF IDs returned are **Disp**, **Temperature** or **HydraulicHead**.

Instead of defining **DOF** for all degrees of freedom at a node, an **DOF** is defined for each individual field variable type. This means a node may contain a list of **DOF** objects with different field types (e.g. for a coupled problem), and an individual **DOF** object can be accessed by its type. The subclasses of **DOF** are related to the actual physical background.

4.4.2.4 Load concept

The term "load" may be defined from a physical or a mathematical point of view. From a physical point of view loads are given by some boundary conditions and change the state of the mechanical system. The actual physical instantiation of a load is highly problem-dependent. In the case of deformation problems, it may be some kind of force. From a mathematical point of view loads appear on the right hand side of the linear equation system.

The class **FemLoad** (c.f. Fig. 18) and its subclasses are used to represent the generic "load" concept mentioned above. The load classes are first hierarchically structured according to geometric characteristics: **NodalLoad** concerns concentrated loads. **ArealLoad** represents distributed loads over element borders. **BodyLoad** captures distributed loads along element boundaries. Since these features are common to all types of loads regardless of the physical backgrounds, they are also considered to be generic classes of the IMAGINE framework. Further, derived subclasses are forced to take physical significance into account. In the case of deformation problems, the subclasses may be **NodalForce**, **ArealForce**, and **GravityForce**.

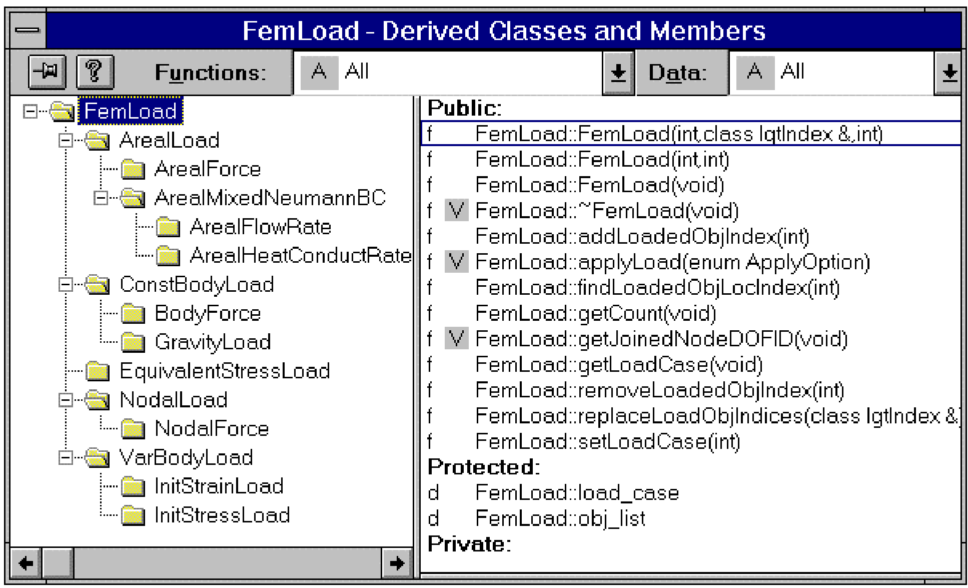


Fig. 18 **FemLoad** hierarchy

The load classes contain information such as where, what and how to apply themselves to the system, usually to **FemNode** objects. They are connected to the system by being derived from **FemSeqObj**. They are linked to appropriate **DOF** objects through the IDs returned from the virtual function **getJointNodeDOFID**.

Each object of **FemLoad** is capable of handling a group of actual loads applied to a group of target objects, as long as the loading specifications remain constant.

4.4.2.5 Constraint concept

The term "constraint" refers to the essential boundary conditions of the governing PDEs of an engineering physical problem. In the case of deformation problems, constraints describe the known boundary displacements.

The abstraction of the constraint concept is done similarly to that of **FemLoad**. Firstly, a **FemConstraint** (Fig. 19) is derived from **FemSeqObj** as a generic constraint data type, which is responsible for "where" to apply the constraints, the subclasses then handle the issues of to "what" and "how" they should be applied. As default, the constraints will be imposed on **DOF** objects.

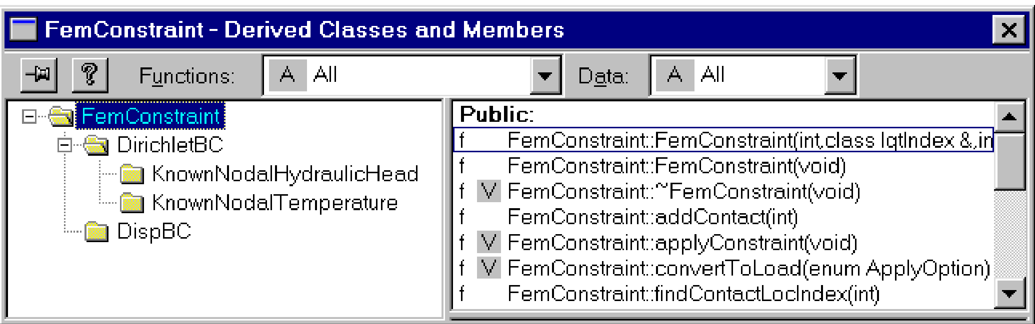


Fig. 19 **FemConstraint** class hierarchy

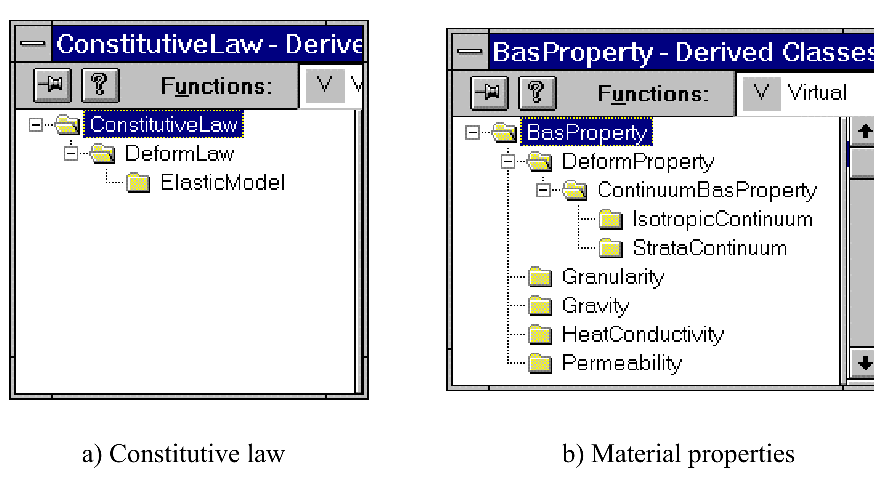
Mathematically, there are two different types of essential boundary conditions: homogeneous and heterogeneous. A constraint is said to be homogeneous when it is zero, otherwise it is heterogeneous. In the case of deformation, the term "constraint" normally refers to the homogeneous ones (i.e. zero displacement), while "prescribed displacement" refers to heterogeneous boundary displacements. Heterogeneous constraints are often considered to be exceptions and to require special treatment both locally and globally. The local treatment that evaluates the contributions of heterogeneous constraints to the "load" vector is handled by **FemConstraint** through the virtual function **convertToLoad**. The global treatment is not a concern of **FemConstraint**.

The class **FemConstraint** has a knowledge of the underlying coordinate system. The constraints of a **FemConstraint** object are considered to be relative to a specific coordinate system. As default, the coordinate system coincides with the global coordinate system. If the constraints of a **FemConstraint** object are not relative to the global coordinate system, information about the local system will then be transferred to the target objects (e.g. **DOF** objects) together with the constraints.

4.4.2.6 Material concept

FE applications can usually be classified according to the type of the governing PDEs, and according to the material behavior. Often, the introduction of a new material model yields a complete new research branch, both mathematically and numerically, even if the underlying PDEs remain the same. Examples hereof are elasticity, elasto-plasticity, and general rheologic behavior.

In OOP, the material behavior forms an independent level of other FE classes: in a strict sense it neither fits in the *project and resource management subsystem* nor in the *FE modeling subsystem*. The reason is that the concept of the material behavior is actually not a part of the principles of FEM, but rather of system states. In fact, the material concept could have been separated from the *FE modeling subsystem* and integrated into a new subsystem. The main reason not to do that but to leave it in the *FE modeling subsystem* was to make it more convenient for other objects of the *FE modeling subsystem* to correspond with it.



a) Constitutive law b) Material properties

Fig. 20 Material concept

The abstractions of the material concerns lead to several class hierarchies in **IMAGINE**: a generic material data type **FemMaterial** (Fig. 15a) in the *modeling class* hierarchy, and a material constitutive law hierarchy **ConstitutiveLaw** and a material property hierarchy **BasProperty** in the field variables hierarchy as shown in Fig. 20.

The class **FemMaterial** serves as a container for material properties and constitutive laws. Various types of material properties and laws can be defined and linked. According to the current design, **FemMaterial** is a kind of architectural class for FE modeling, while material **ConstitutiveLaw** and material **BasProperty** are kinds of architecture classes pertaining to field variables.
Since class **FemMaterial** is derived from **FemSeqObj** it inherits the integrity of modeling objects established by **FemSeqObj**. It is accessible directly by other modeling objects. The objects of **ConstitutiveLaw** and **BasProperty** can be accessed with their **FemMaterialLawID** and **FemMaterialPropertyID**.

Because a given application domain may contain several material laws for each computational step, several material laws may be stored in the **FemMaterial** object. However, all the **FieldVar** objects and even class **FemStruct** will ignore which material law should be applied and when it should be activated. The material concept as it is implemented in IMAGINE is tightly connected to the concept of computing tasks as modeled by the classes **FemAnalysis**, **FemTask** and **FemTaskCmd**.

A material may have many physical properties, e.g. deformation properties, permeability, heat conductivity, gravity, granularity[1]. They are material attributes and measurable under normal conditions. These basic properties are abstracted with class **BasProperty** and its derived classes. The class **BasProperty** itself is one of the architectural classes for the physical field system. It is not instantiable directly. More detailed information, such as property type and property constants, are supposed to be the responsibilities of its subclasses. Fig. 20b) shows the current five direct branches of class **BasProperty**: **DeformProperty**, **Permeability**, **HeatConductivity**, **Granularity**, and **Gravity**. Other properties can be defined on demand.

The class **ConstitutiveLaw** and its derived classes are used to describe the physical relationship of more complex material behavior than can be expressed with the basic properties. **ConstitutiveLaw** is derived from **FieldVar**. It is therefore also a kind of architectural class for the physical field. Like other **FieldVar** classes, **ConstitutiveLaw** has its associated **FieldVar** classes and can be accessed by other **FieldVar** objects through its field variable type ID. A set of basic interfaces to other objects of the *FE modeling subsystem*, such as **D** and **C** matrices, have been prototyped which are considered to be common to all material models. It is the responsibility of the subclasses to implement them.

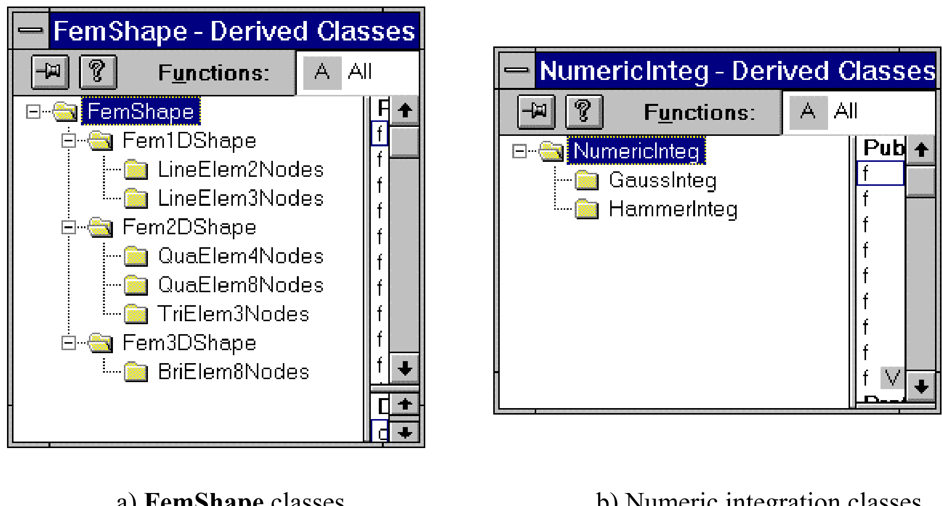
Normally, the behavior of a material depends on the state of the field variables and the path which led to them. However, in IMAGINE it is not the responsibility of the material objects to trace this information, but rather the responsibility of **CFemProject** and **FemAnalysis**.

4.4.3 Numerical classes

Numerical classes are primarily responsible for providing integration support for **FemElem.**
In FEM, due to the mathematical complexity, element analysis (e.g. integration, derivation, etc.) is usually not done directly in the physical space of the element. Instead, some standard and regular element shapes are provided in a mapped space in form of standard shape templates. Each element template is defined by a set of shape functions. The shape functions depend on the dimensions of the mapped space, and the number of nodes of the shape template. Element analysis is then done in the mapped space and is subsequently remapped by means of coordinate transformations.

[1] In "granularity" the cohesion and the angle of friction are comprised.

In IMAGINE, the shape information, both geometrical and analytical, are abstracted and modeled by the **FemShape** class hierarchy, as shown in Fig. 21.



a) **FemShape** classes b) Numeric integration classes

Fig. 21 **FemShape** class hierarchy

The class **FemShape** and its immediate subclasses **Fem1DShape**, **Fem2DShape** and **Fem3DShape** are defined as abstract classes, i.e. they just serve as generic classes which cannot be instantiated. Derived classes of them are the actual shape templates which are responsible to provide detailed information.

In addition to local geometric information, other important information that **FemShape** (and its subclasses) is expected to provide is local topological information and local analytical information.
Local topological information include local indexed face-side-vertex structures. It is predefined for every shape template. This information is often needed to perform some kind of integration over the boundaries of an element's shape template, e.g. the calculation of distributed loads.
Local analytical information of a shape template refers to its shape functions and the derivatives of these shape functions at given points of the shape. The shape functions are predefined for every instance of a shape using class **ArrayPartial** which is capable of returning the partial derivatives if the corresponding functions are given. From the viewpoint of element analysis, two set of points of a shape template are considered of special importance: the integration points which are needed to compute the element stiffness matrix; and the points where field variables are computed. The numerical integration scheme, including the integration points and weights, are abstracted in class **NumericInteg**. Objects of **NumerInteg** are expected to be specified by users (programmers) and used by **FemShape**. All the local analytical information is computed only once at the integration points as long as the points remain unchanged.

The mapping information, such as the Jacobean determinant, can be computed when global coordinates are given. The nodal global coordinates are considered to be the concern of **FemElem** and will be supplied by the objects of **FemElem**.

Once an element shape is defined which may be instanced, it can be used for all physical field problems thus avoiding coding redundancy. Once an object of element shape is created, it will be shared by all element objects with that shape without repeated computation of local analytical information for an element object, which leads to both programming efficiency and computing efficiency.

4.4.4 Global representations

So far great effort has been made to separate the various responsibilities of FEM as much as possible. A set of architectural classes at the local (discretized) level has been established which addresses the individual concepts of FEM. However, a discretized FE system is a discretized representation of the original PDEs for the overall (global) geometric definition domain. All the local objects are just parts of the global system and must be compiled to build up the global representation. The discretized FE representation in terms of local objects is abstracted in class **FemStruct** (Fig. 22).

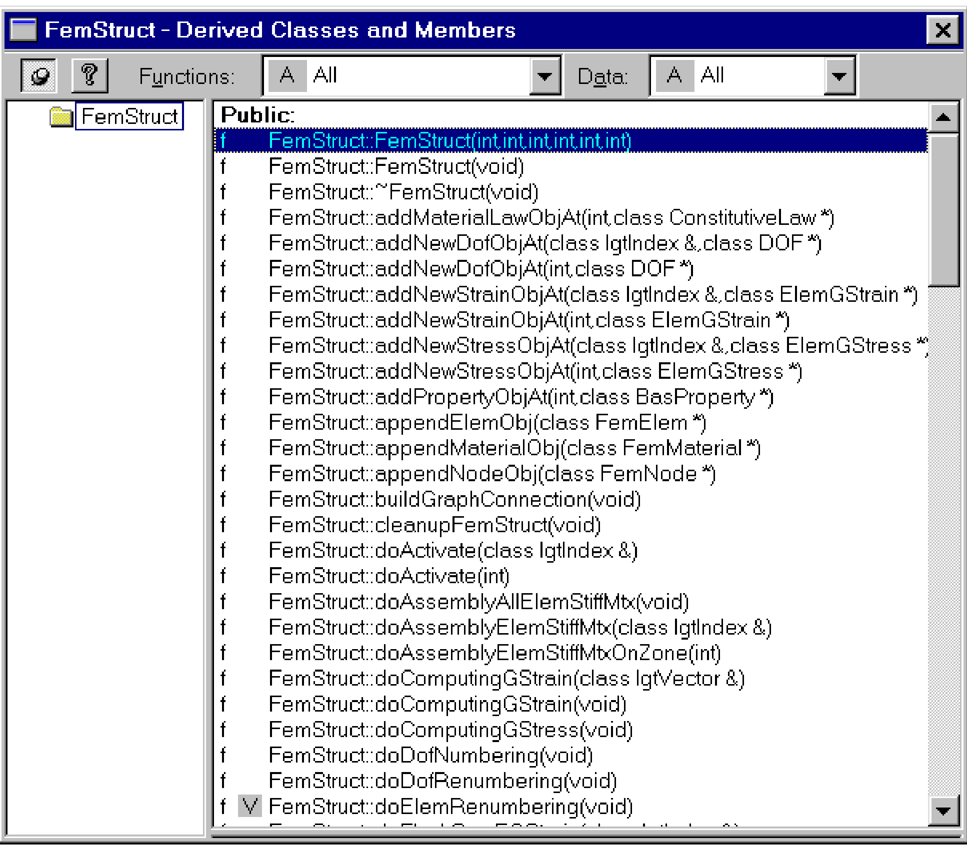


Fig. 22 Representation of the discretized FE system in **FemStruct**

Class **FemStruct** is the abstraction of a generic FE system. The term "Struct" refers to the discretized FE representation, not to the concept of an engineering structure, although **FemStruct** can be created as the discretized FE representation of an engineering structure.

The most important components of **FemStruct** are **FemElem**, **FemNode** and **FemMaterial**. IMAGINE is based on the requirement that the components are properly created outside of

FemStruct, because **FemStruct** has no knowledge neither about the type of an element, nor about the type of the physical variable acting in it. The creation and initialization of the objects is considered to be the responsibility of **CFemProject** (for element types, DOF types, state variable types, material property types, coordinates, etc.), which acts as the bridge between the original geometrical and physical specifications and the FE representation, and the responsibility of **FemAnalysis** and **FemTask** (for loads and constraints, material laws), which specify various boundary conditions and computational tasks. The sequence in which the objects are added to **FemStruct** is not significant.

Thanks to the complete separation of modeling components and field variable components of IMAGINE, it is possible to create a **FemStruct** object with the complete information about the geometry and topology of the discretized system, but without any field variable objects attached to it. The field variable objects, such as **DOF**, **ElemGStress**, **ElemGStrain**, **BasProperty**, **ConstitutiveLaw**, etc., can be bound later to the **FemStruct** objects on the fly without influencing the topological structure of **FemStruct**. This may be useful for a case where one physical problem has to be determined as the initial condition of another. As an example, the case may serve where seepage forces act as loads for subsequent stress calculations.

The topologic relations are the main concern of **FemStruct**. These include element-node graphs and DOF numbering. The relations will be built or rebuilt by **FemStruct** after proper initialization or change of specific components. These relations may be completely hidden to outside classes. E.g. optimization of node or element numbering schemes is considered to be the internal affair of **FemStruct**.

FemStruct does not store any of the objects of **FemLoad** and **FemConstraint**. They are realized as modeling classes in the sense of boundary conditions which are managed by **FemAnalysis** and **FemTask**. They are applied to **FemStruct** on demand. It is the responsibility of the task scheduler to specify correctly which boundary conditions apply before solving the system.

Besides **FemStruct**, the other important class hierarchy which is responsible for global concerns is **FemSolver** (Fig. 23). It contains a hierarchy of various type of solvers, and all methods which depend on these types, including assembling the global stiffness matrix based on the local data of **FemStruct** and solving the system of equations. Currently, just a basic skyline solver, a representative of direct solvers, is used. However, provisions have been made and implementation has been started to include also iterative solvers, such as the conjugate gradient method (Crisfield, 1986). Iterative solvers seem to be especially well-suited to 3D problems or for use in conjunction with an adaptive mesh refinement.

Fig. 23 Solver classes

4.4.5 Basic classes

Often IMAGINE needs to manipulate, to operate on and to represent modeling objects like elements and nodes and field variable objects like stress and strain. For this purpose, a set of basic matrix and geometric data types has been designed to cover fundamental geometric and algebraic requirements, including:

- location and coordinate classes: **IgtPoint**, **IgtCoOrd**, **PolarCoOrd**, **CylindCoOrd,**
- coordinate system classes: **IgtCoOrdSys**, **IgtOrient,**
- data representation classes: **IgtMatrix**, **IgtVector**, **IgtIndex.**

The role of the data types representing coordinates and coordinate systems are obvious and need no special comments. E.g. **IgtPoint** abstracts a geometric location in space. It is transformable (from one geometric configuration to another) and operable (add, subtract, etc.). **IgtCoOrdSys** is used in classes **FemElem**, **DOF**, **FemConstraint** and **FemMaterial** to specify their own local coordinate systems if required.

The design of the matrix classes requires some additional comments. Matrices are often classified according to their element distribution characteristics. Examples of this are triangular matrices, banded matrices, sparse matrices, symmetric matrices, etc. In order to save system resources and to promote computing efficiency, it is desirable that a matrix "knows" its type, how to store its data and how to execute common operations. Often OOP is cited as a good candidate to reach these goals thanks to its inherent capability of data abstraction and polymorphism.

With respect to the size of the matrices, IMAGINE relies on two completely different matrix types. The global stiffness matrix is usually quite big (several thousand degrees of freedom), whereas the local matrices (such as coordinates, stress and strain vectors, and all the matrices needed for the element analysis) are very small. The problems of these two matrix types are rather different. The main problems when working with large matrices are how to allocate and handle storage (virtual memory!), and to find the most efficient solving algorithm according to their data structure. Both problems are irrelevant for small matrices. However, here the main problem is to avoid unnecessary overheads for frequent allocations and deallocations of small memory chunks, something which in turn is not relevant for large-size matrices.

From a conceptual point of view it would be tempting to have a common matrix hierarchy that covers the concerns of all matrix types. Two arguments are opposed to this approach: Firstly, as mentioned above the demands on large and small matrices are completely different. Therefore, the corresponding classes would have just a very small common basis. Secondly, compatibility requirements between the different matrix types, e.g. automatic type conversions, would lead to a lot of work and unnecessary overheads, which would then lead to inefficient algorithms.

Therefore, IMAGINE relies on two completely separated matrix concepts. Large matrices are used and handled in the context of **FemSolver.** Small matrices as needed for local operations are abstracted in the classes **IgtMatrix** and **IgtVector**.

IgtMatrix and **IgtVector** are used by many classes of IMAGINE: the FE modeling classes, field variable classes, and the geometric modeling classes. They are designed to address the above mentioned concerns of small matrices.
An effort has been made to avoid unnecessary allocation and deallocation overheads during matrix operations. Consider, for examples, the formation of the element stiffness matrix ***K = (~B) * D * B*** where operator ~ stands for the matrix transpose. In C++, normally a temporary matrix (not pointer), say ***BD***, will be allocated and initialized with the matrix returned from ***(~B)*D***, say ***returnMatrix***. The ***returnMatrix*** will then be deallocated. This kind of allocation-initialization-deallocation happens in all cases of matrix or vector operations that return a matrix or a vector data type. Since the matrix or vector operations are intensively used in FEM, it is very important to avoid the aforementioned redundant allocation-initialization-deallocation procedure. This may be achieved by introducing a reference counter in class **IgtMatrix** and **IgtVector** to control the redundant allocation-initialization-deallocation. In the above case, the data representation of ***BD*** will be linked to ***returnMatrix*** and inform ***returnMatrix*** that its data is referenced. The data of ***returnMatrix*** will not be deleted when the destructor of ***returnMatrix*** is called. In this way no redundant allocation-initialization-deallocation is taking place, thereby greatly enhancing the computing efficiency.

5 Design and implementation of the user interface

5.1 Introduction

IMAGINE is rather a framework than an application. Although it provides classes ranging from FE modeling, meshing, solvers to task control, it does not give users the option of inputting data and outputting results, as would be the case for an application.

With increasing size of framework, sometimes it is no longer so apparent why individual classes have been provided and how they should be used. Therefore there is a strong need for a possibility which allows exploring the features of IMAGINE. Conventionally such a possibility consists of some simple example applications. However, because with IMAGINE a variety of applications can be implemented, we pursue another approach. An integrated modeling and controlling environment is presented which serves as a quite general and extendable user interface for defining and running examples with IMAGINE. Its design follows closely the design of IMAGINE itself in order to demonstrate as far as possible IMAGINE's class layout and features.

The aim of this modeling and controlling environment is twofold: first fulfilling the requirement, according to which three applications of a framework are necessary to validate its strategic and tactical decisions (Wirfs-Brock, 1990, cited by Booch, 1994).
And second, perhaps more important, to demonstrate that the object-oriented design of the framework may also be (partly) continued for the user interface, in the sense that the user may choose objects (e.g. a node) and subject them to methods (e.g. apply a load).

5.2 Workbench approach

5.2.1 Overview

As shown in Fig. 4 "General class architecture", IMAGINE is made up of two main subsystems. One is the *project and resource management subsystem*, the other the *FE-modeling subsystem*.

Each subsystem is structured into further subsystems. The *project and resource management subsystem*, for example, contains the subsystems *project view and control*, *geometric modeling, resources and their management* and *task control*. Of special interest with regard to the design of the user interface is the subsystem *project view and control*. It contains the root of the whole architecture, the class **CFemProject**, which abstracts the domain of all data of an **FE** analysis project, together with its manipulations.

As mentioned above, this domain is completely separated from the view of the data. The view concept comprehends not only organizing the actual display of the data, but also orchestrating all user interactions which could change the display either directly or by changing the underlying data. This concept relies on the *Document-View Concept* of the MFC (c.f. "Appendix 3: The Document-View Concept of the MFC").

Class **CFemProject** acts as the interface between the generalized data and their view. The view itself is managed by so called workbenches. At the moment, three workbenches are defined: the *Geometric Modeling Workbench*, the *Fem Modeling Workbench*, and the *Fem Task Workbench* (see Fig. 24). The *Geometric Modeling Workbench* is used to define and edit the geometry of the

project by means of solid modeling. Currently, as outlined in section 3.7, external solid modelers are used instead of this workbench. In the *Fem Modeling Workbench* all the FE resources, including the mesh, may be defined and modified. The *Fem Task Workbench* provides a graphics editor, in which the computational tasks may be defined and assembled into a kind of a flowchart. A fourth workbench, which could be added in the future could be used for postprocessing and displaying results. At the moment, this is delegated to third party software (see section 3.8).

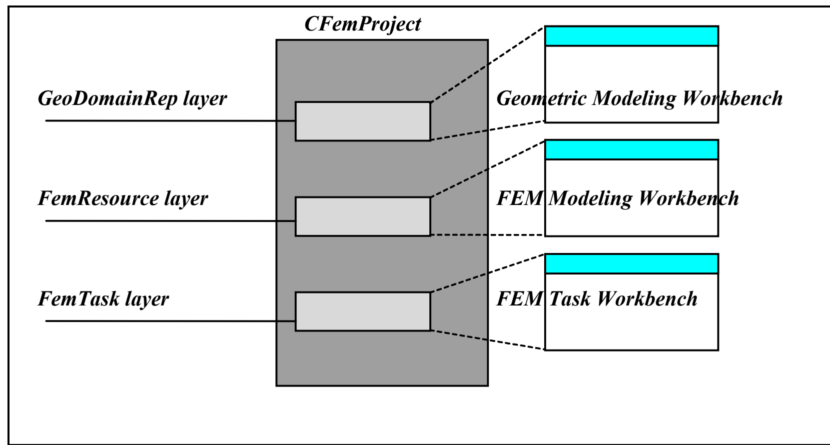


Fig. 24 IMAGINE workbenches

Each workbench is abstracted by a corresponding class (Fig. 25). It may be seen, that the design of IMAGINE's workbenches follows closely the architecture of IMAGINE's design (c.f. Fig. 4).

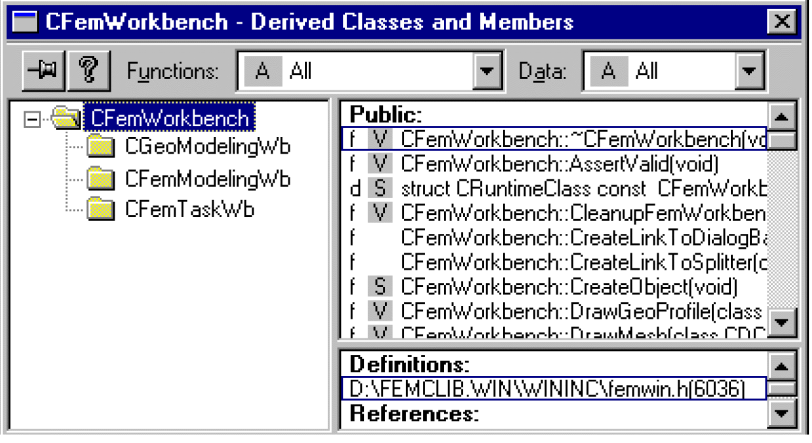


Fig. 25 Workbench classes

5.2.2 *Kinds of workbenches*

An important task of each workbench is to provide the means for a straightforward definition of resources. According to their domain of validity three classes of resources are distinguished:

- project resources, which apply at the "project level", where the geometry is described by a solid model, a quadtree or a superelement representation,
- FE resources, which apply at the discretized "FE level", and
- task resources, which apply independently of the above mentioned levels for the analysis directly.

Striking examples of project resources are obviously geometric data at the non discretized level, abstracted at its highest level by **GeoDomainRep**, but also modeling attributes which depend on location, as e.g. zones, material properties, loads and constraints, which are abstracted by **FemMaterial**, **FemLoad, FemConstraint**, etc.

Examples of FE resources are structural resources (e.g. nodes, elements, topology, abstracted by **FemNode**, **FemElem, FemStruct**, etc.), and all types of physical field resources (e.g. displacements, stresses, abstracted by **FieldVar**, DOF, **StateVar**, **ElemStateVar**, **BasProperty** and **ConstitutiveLaw**, etc.).

As already mentioned, even the definition and control of computational tasks adheres, in contrast to conventional designs, to the object-oriented approach. Therefore resources for tasks are defined, e.g. analysis properties, applicable commands etc., which are abstracted at the uppermost levels by **FemAnalysis**, **FemTask** and **FemTaskCmd.**

This distinction of resources at the project level from the FE level provides a great flexibility not only for the input, but also for the execution process.
Only project resources must be defined explicitly. However because their number is much smaller than the number of FE resources, their definition is much simpler and more straightforward. Furthermore it enables a more intuitive way to simulate a complex engineering analysis. The meshing process can be carried out without having to come back to the definition of input data. This forms the foundation for an adaptive mesh refinement during an analysis.

Apart from the solid modeler itself, project resources are defined at the *Fem Modeling Workbench*, and task resources at the *Fem Task Workbench***.**

FE resources, which apply at the discretized "FE level", do not have to be defined explicitly. Structural resources are defined automatically during meshing. **FemStruct** is responsible for managing these resources, and also to get the necessary data from **GeoDomainRep**. On the other hand, **GeoDomainRep** is able to query **FemStruct** for geometric objects. Thus, a zone object "knows" all the elements and nodes that belong to it, or a curve object knows which elements it intersects and which nodes lie on it. This is an important design property. It can be used to assign project resources to discretized elements and nodes. Additionally it may serve to group elements and nodes for postprocessing purposes.
Physical field resources are defined automatically during execution. They are bound to the **FemStruct** objects dynamically.

5.2.3 Layout of a workbench

Three requirements should be fulfilled by a workbench: firstly an area must be separated, which serves for visualizing the geometry, the topology and the properties of the target engineering problem. Secondly, visualized objects should be selectable and be able to be subjected to methods (actions), so that resources may be quantified and stored. And thirdly, forms are required by which the properties of the resources may be input.
All three parts should interact accordingly, so that for selected objects only appropriate methods may be applied, and for specific methods only valid attributes may be chosen.

Fig. 26 illustrates the approach adopted in IMAGINE. It shows the *Fem Modeling Workbench* displaying a cut-and-cover tunnel project. The main window of the workbench is split into four parts, so called frames: the *View Toolbar* at the top, the *Selection Frame* at the left, the *View Frame* in the center and the *Form Frame* at the right.

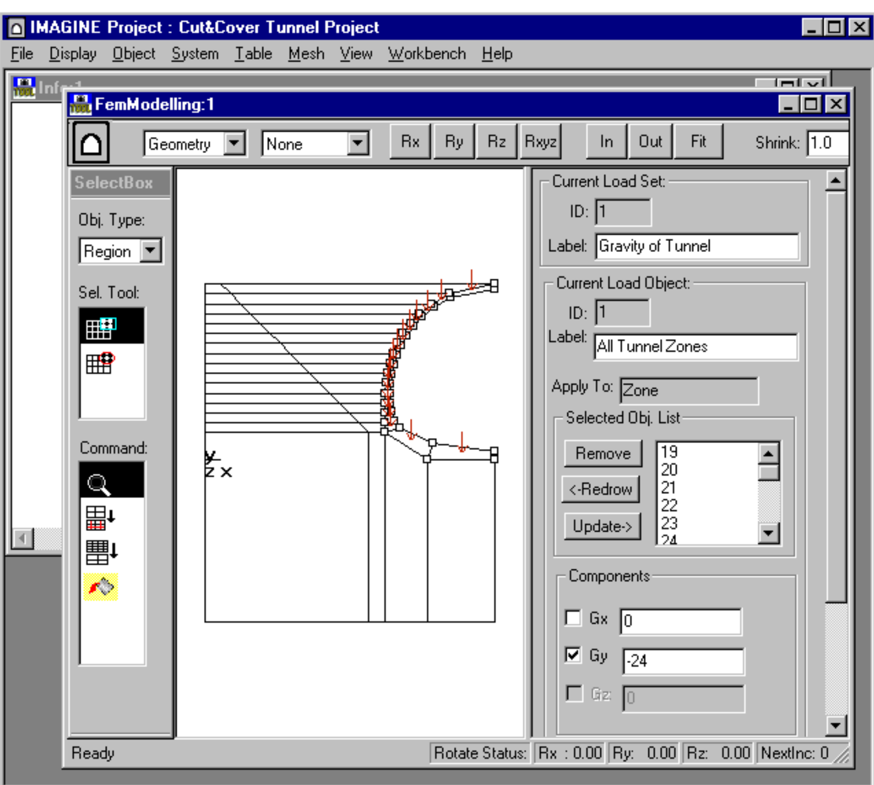


Fig. 26 Layout of an IMAGINE workbench

The *View Toolbar* is used to specify what to view and how to view it, e.g. the geometry profile - from the front.
With the *Selection Frame* selection properties are defined, first the type of object which should be selected ("Region" in Fig. 26). In the box below the valid selection tools for the chosen object type are displayed, e.g. the point selection tool for selecting individual objects, or the rectangle or circle selection tool, for selecting objects in a certain area. The selection itself is executed graphically in the *View Frame*.

Also in the *Selection Frame*, depending on the selected object type, the methods (i.e. commands) are listed, to which the selected objects may be subjected. These methods are applied by double clicking them with the mouse.
In the *View Frame* the geometry, mesh, various properties and resources may be visualized. Objects in this frame may be selected for applying methods.
Finally the *Form Frame* is used to define the properties of the selected objects. For each workbench a set of input forms is provided to interact with all objects.

The *Fem Task Workbench* uses the same frame design. There, the *Form Frame* is used to define the properties of analysis and task objects. This will be described later in this report.

The master window of all workbenches is of type Multiple Document Interface (MDI). This allows several windows to be created concurrently. Semaphores are used for coordinating them.

5.3 Fem Modeling Workbench

5.3.1 Geometric resources at the project level

As described in section 4.3.2 "Geometric modeling", IMAGINE relies on **GeoDomainRep** to deal with geometric related data and operation. **GeoDomainRep** is capable of querying, computing and spatial decomposition. This makes the graphical manipulations of geometric objects much easier since here one only has to concentrate on the user interface itself, without being distracted by how to implement the desired operations.

Assigning resources to geometric objects starts with specifying the type of geometric objects to be selected. The valid object types appear automatically in the corresponding drop down box. For the 2D case the valid object types are *Region*, *Vertex*, *Curve, Surface*, and *Zone*. Fig. 27 shows these types together with the corresponding selection tools and methods (commands) which may be applied (*Surface* is in this respect the same as *Curve* and is therefore not shown).

When choosing object type *Region* (Fig. 27a), one can select, e.g. a rectangular part of the structure (i.e. a region). In the *View Frame* the chosen objects are displayed, in the case of a *Region* just a dotted rectangle. To this region certain methods may be applied. The valid methods for type *Region* are *Zoom*, *Refine*, *Unrefine* and *Color*. I.e., such a region may be zoomed in, refined or unrefined (in the case of a mesh), or colored to highlight it. An example of mesh refinement is shown in Fig. 64.

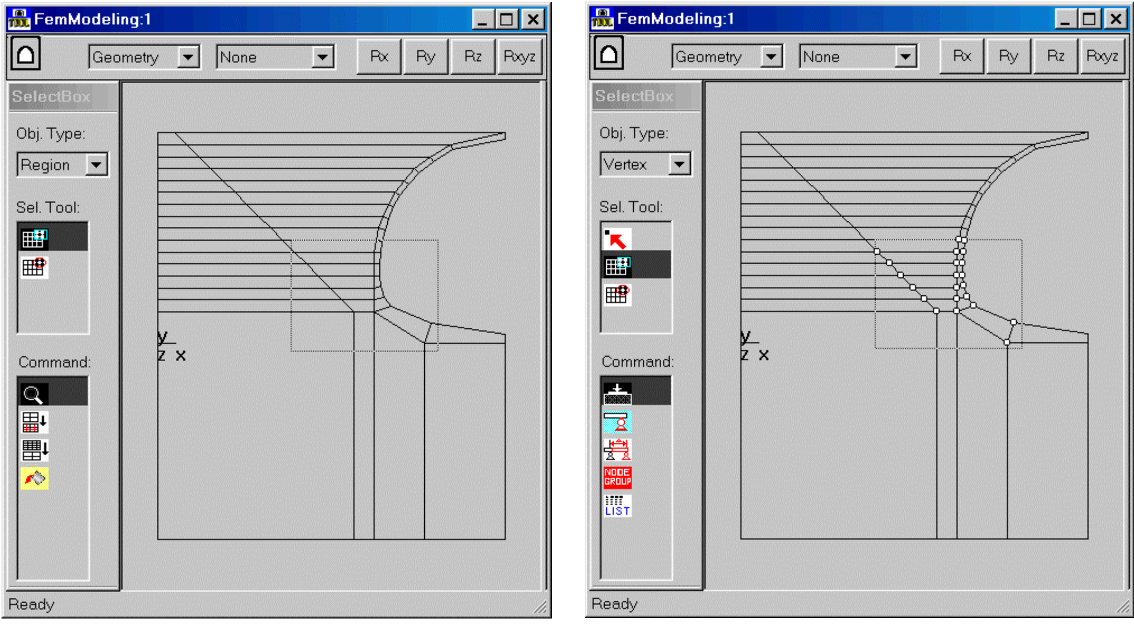
In Fig. 27b a set of *Vertex* objects has been selected. The associated command list allows to apply concentrated loads, support conditions (i.e. constraints) or prescribed displacements to these vertices. Additionally it is possible to assemble vertices in specific vertex groups. Such groups are then treated as independent objects which can be used when defining individual tasks (c.f. 5.4: "Fem Task Workbench"). In this way the state of stress or displacements may be inspected specifically for selected vertices.
The last applicable command for *Vertex* objects is *List*, which allows immediate display of their properties.

In Fig. 27c a set of *Curve* objects has been selected. *Curve* designates edges of solids or superelements. In the *View Frame* they are marked by small circles in the middle of the edges. Curves may be subjected to methods to assign distributed loads and loads equivalent to a

prescribed state of stress. The latter method allows one to simulate an excavation starting from a primary state of stress, which is defined purely analytically.
Also curves, as well as vertices, may be subjected to prescribed constraints and displacements. The vertices and elements which are part of a curve may be assembled to groups and their properties may be listed.

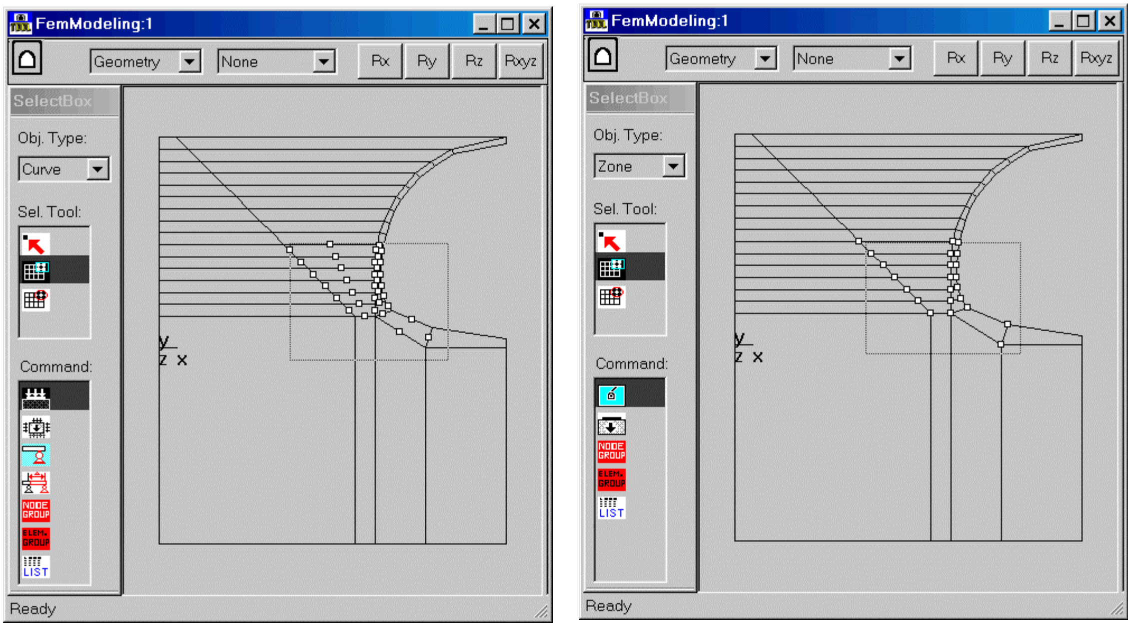
The use of *Surface* objects is similar to that of *Curve* objects. The main difference is that *Surface* objects designate areas and not edges. Therefore when applying a prescribed state of stress the whole area is subjected to this state. This property allows one to assign an analytical primary state of stress, without executing an FE computation. An additional advantage is that in this way arbitrary coefficients of lateral pressure may be prescribed without time-consuming FE computations.

The last available object type is *Zone* (Fig. 27d). In the 2D case a zone is a face of a solid or a part of a superelement. A zone serves to describe values which apply to areas in 2D or bodies in 3D. Prominent examples are material properties or the dead weight.
Similarly to above, the vertices and elements which are part of a zone may be assembled into groups and their properties may be listed.



a) Object type *Region*

b) Object type *Vertex*



c) Object type *Curve*

d) Object type *Zone*

Fig. 27 Selection of geometric objects

When subjecting a geometric object to one of the methods mentioned above, a form pops up in the *Form Frame*, in which the resources, e.g. material properties, may be defined. This is described in the following section.

5.3.2 *Modeling resources at the project level*

5.3.2.1 *Design of the interface*

The design and management of IMAGINE's project resources is described in section 4.3.3 and visualized in Fig. 9. In the current section the creation and the graphic user interfaces of project resources is discussed. The main task of the interface is to provide a connection to the underlying resource database.

The resource database is accessible from all workbenches. For the *Fem Modeling Workbench*, the interface between the resource database and the geometric objects is of particular interest since most resources are defined for specific geometric objects. This interface may be displayed in the *Form Frame* at different hierarchical levels, where the attributes of objects are displayed, and where they may also be edited.

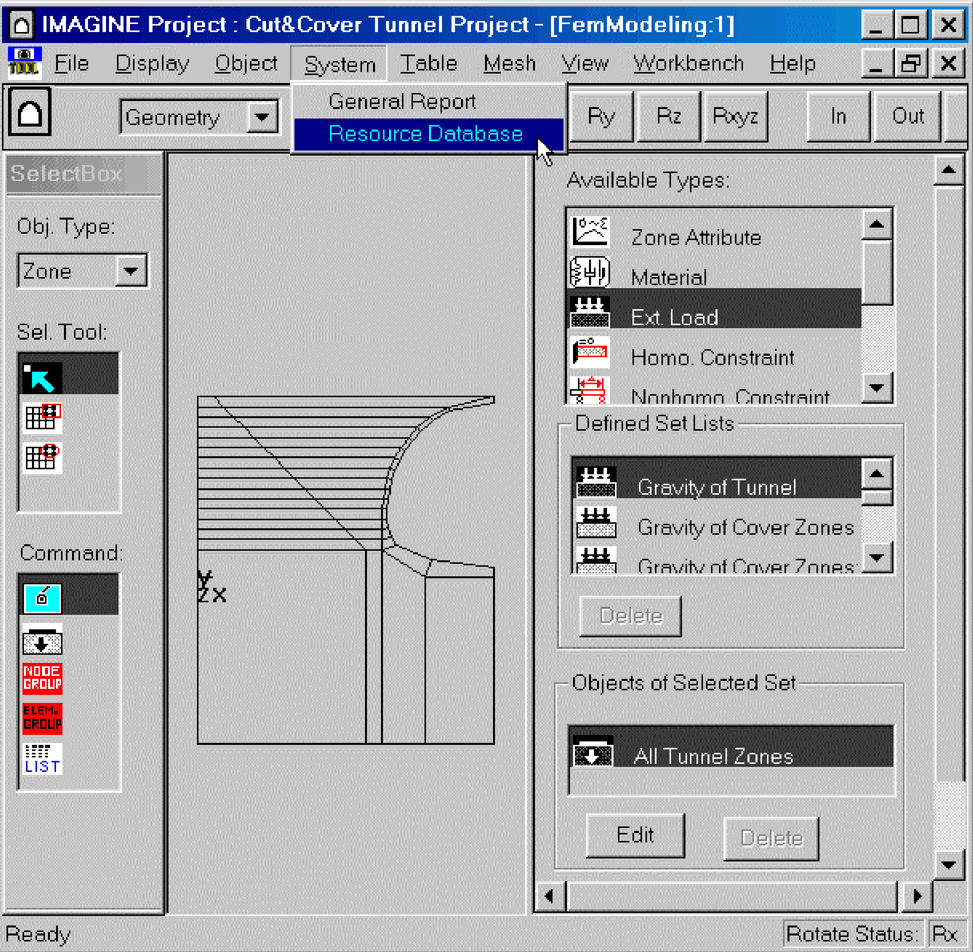


Fig. 28 Interface to the resource database

As an example, Fig. 28 visualizes the database at its highest level. The uppermost listbox named "Available Types" displays the different types of resource classes available[1]. When selecting a

[1] In this context, "available" always means implemented in IMAGINE, whereas "defined" means created by a user while working with the current project.

resource type, the listbox in the middle displays the currently defined sets for this type of resource. These sets are just containers for resource objects of the same type. They provide another level of grouping objects, which will be especially useful when defining task objects (c.f. 5.4. "Fem Task Workbench").
After selecting a set, the listbox at the bottom displays all objects pertaining to this set. These objects are consequently all of the same resource type. Finally each of these objects may be edited, i.e. its properties may be changed.
Thanks to this design, any resource object that has been created and stored in the resource database may be selected and edited using this resource database interface.

Another way that leads in the end to the same object property form is to concentrate on geometric objects and to apply resources to them via commands, as outlined in the previous section 5.3.1. In this case one would first select some geometric objects via the *Selection Frame* and the *View Frame*, e.g. a zone in Fig. 28, and then apply the desired command (e.g. "dead weight"), after which a new or an existing resource set may be chosen. To this set a new resource object is added, which is displayed in the *Form Frame*.
This more visual approach may be circumvented by choosing menu option *Object*, which leads first to some dialog boxes (see 5.3.2.2 "Resource forms"), and finally again to the same edit form as above.

As far as the implementation is concerned, IMAGINE uses a hierarchy of forms as interface to the resource database. All forms are derived from base class **CFModHelp** (Fig. 29). **CFModeHelp** is a windows object that hosts the form panel of the *Fem Modeling Workbench*. The interactions with other frames of the *Fem Modeling Workbench* are managed at the **FmodHelp** level. The derived resource forms are mainly responsible for the resource objects themselves, but not for windows management.

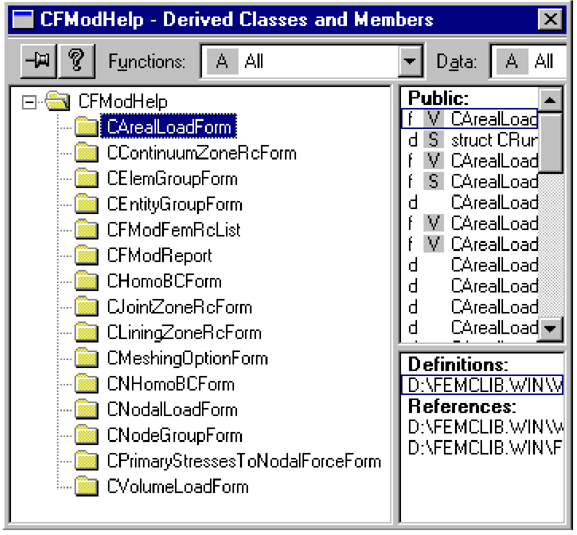


Fig. 29 Resource form hierarchy

5.3.2.2 Resource forms

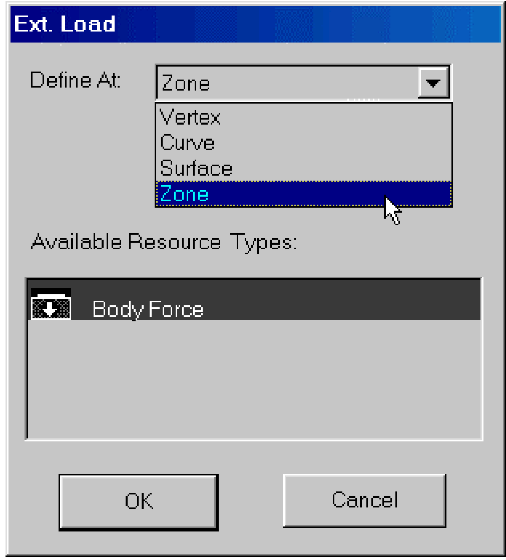
In this section, the main resource object forms will be presented, i.e. forms for

- external loads,
- constraints, and
- zone attributes and material properties.

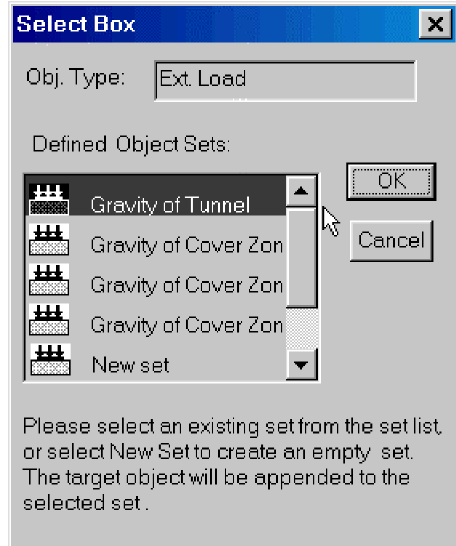
The process of creating new resource objects always follows the same procedure. It will first be demonstrated for a load object. A new resource object may be created e.g. by choosing menu option *Object*, *External Load*. The load is called "external" because it does not originate from state variables such as primary stresses. External loads may be applied to a vertex (concentrated load), to a curve or a surface (distributed load), or to a zone (body load, e.g. dead weight). The dialog box of Fig. 30a) displays for each target the available resource types, from which one may be selected. For the selected type the load sets already defined are displayed in Fig. 30b). It is then possible to choose a defined set or to create a new one. In either case the resource form for a new load object is displayed in the *Form Frame*. This object is appended to the list of the chosen load set.

In the load resource form of Fig. 30c), at the top the name of the load set is listed to which the current load object belongs. At the bottom, the properties of the load object may be input, in the present case the components of gravity. Additional properties of this load object are the objects, in which the load is acting, i.e. the zones, in which gravity applies. These are listed in the middle of the resource form under the heading *Selected Object List*. They have been selected before with the mouse in the *View Frame*. These zones are marked by small circles at their limiting vertices (Fig. 31). Additionally arrows have been drawn representing the individual gravity loads. For better viewing a part of the geometry has been zoomed and the zone numbers have been captioned.

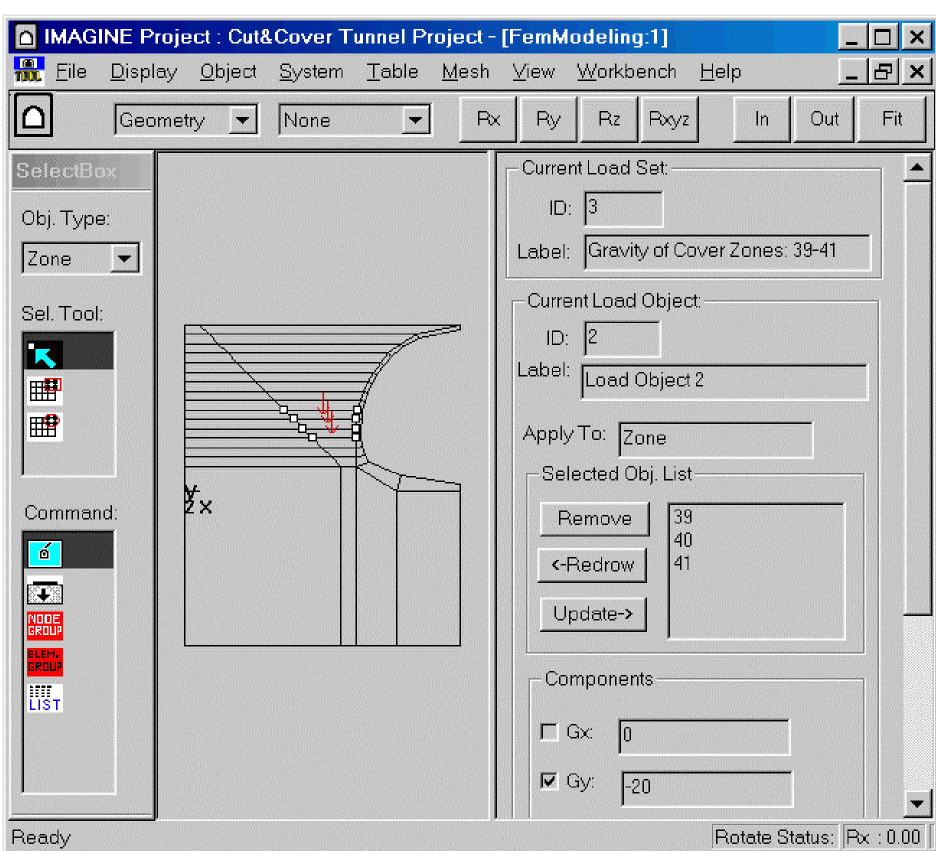
As a second example the creation of a constraint object is illustrated. Two types of constraints are available, homogeneous and heterogeneous constraints. In a deformation analysis homogeneous constraints are equivalent to rigid support conditions, whereas heterogeneous constraints refer to prescribed displacements.
Constraints may be applied to vertices or curves (Fig. 32a). In part b) of this figure the constraint resource form is displayed, with the constraints of no displacements in x-direction applied to the curves forming the left boundary. A further attribute which can be defined for a constraint object is the coordinate system. This is also an object, which may be defined separately. Here the global coordinate system has been selected. However it would be possible to use another coordinate system, which could be useful for inclined supports.



a) Available types of external loads



b) Defined load sets



c) External load resource form

Fig. 30 Creation of a load object

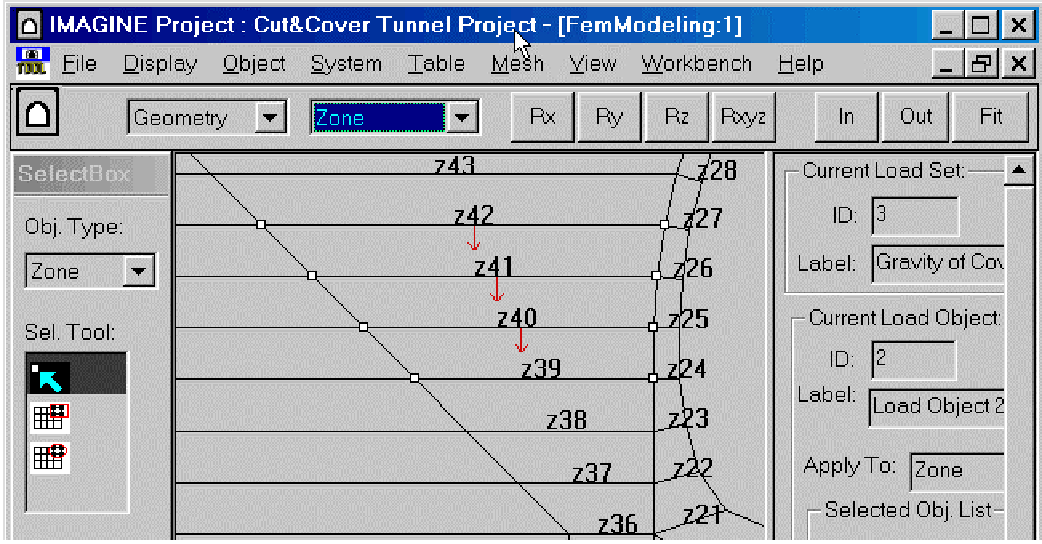
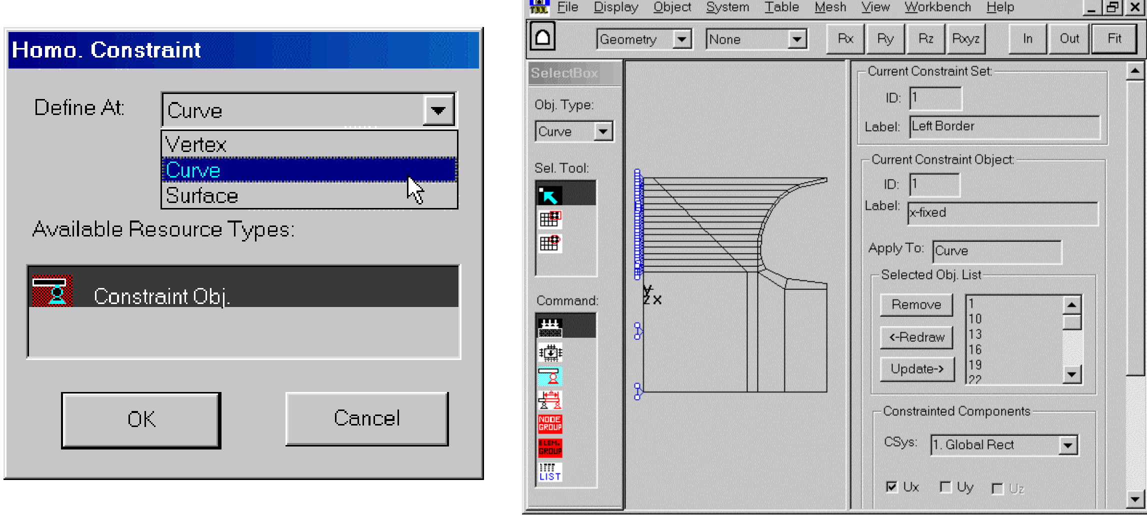


Fig. 31 Zoomed detail of Fig. 30



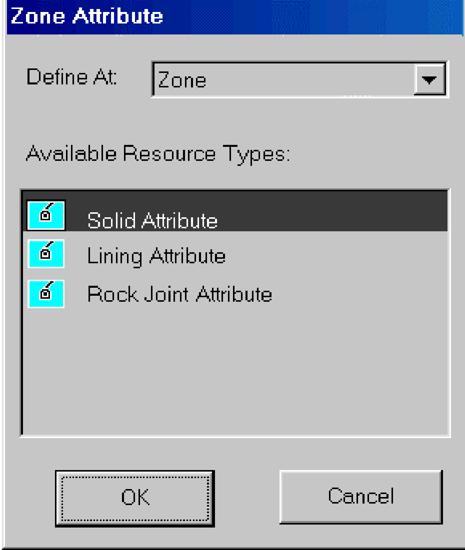
a) Available types of constraints b) Constraint resource form

Fig. 32 Creation of a constraint object

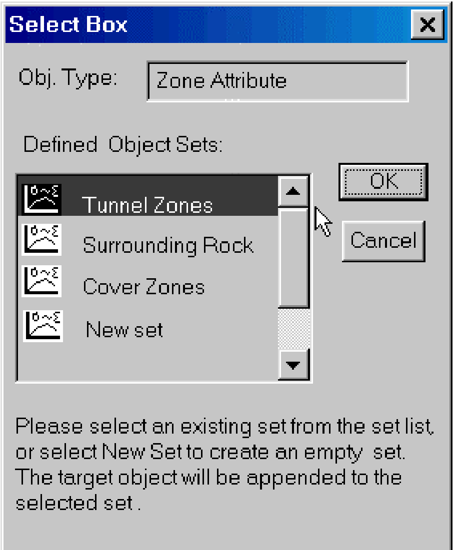
It should be noticed, that the attributes of a constraint object are not single values only as in the case of a load object, but may also be an independent embedded object (the coordinate system).

For the case of the next example, a zone attribute object, this is taken to the extreme, in that the attributes consist of embedded object sets.
Remember: zone attributes and material properties are closely related resource types (c.f. section 4.3.3). Zone attributes include types of zones (e.g. a lining zone) and types of materials (material properties and material laws). Therefore a set of zone attributes is defined as one type of zone associated with a material set. The latter may contain several material objects.

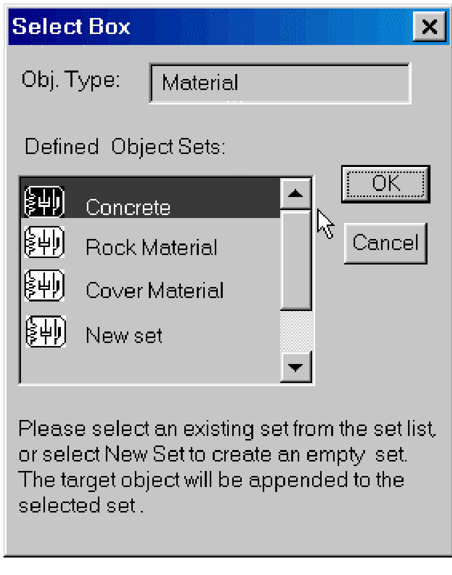
We shall explain this in an example. When creating a new zone attribute object, first the desired type, e.g. a solid zone, must be selected (Fig. 33a). Then one has the possibility to select an existing or new zone set (Fig. 33b). Because zone objects contain associated material sets, a material set must be chosen (Fig. 33c). These sets have been defined before based on a certain material type (Fig. 33d).
Finally the resource forms for the zone set and possibly for the material object are displayed (Fig. 33e and f).



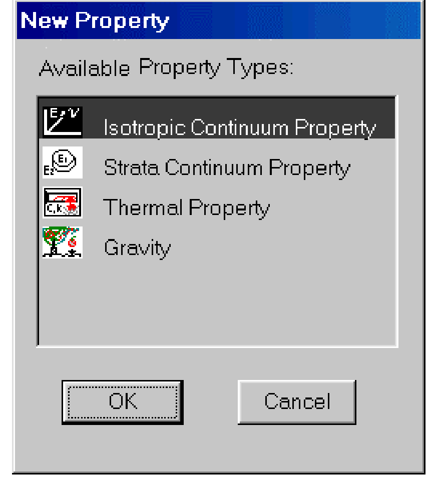
a) Available types of zone attributes



b) Defined zone sets

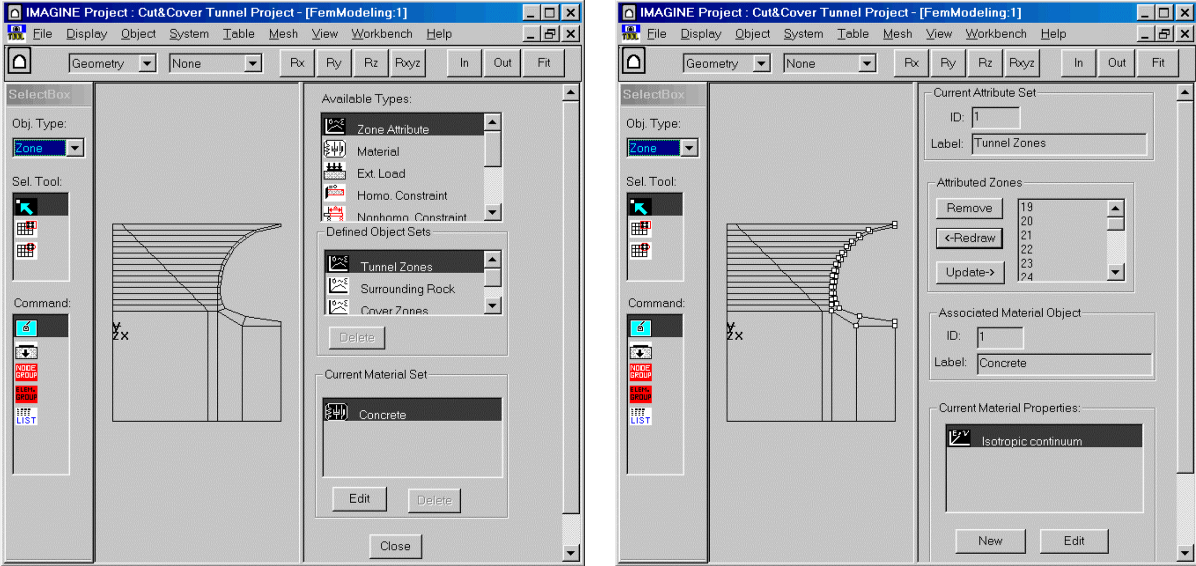


c) Defined material sets



d) Available material types

Fig. 33 Creation of a zone attribute object (part I)

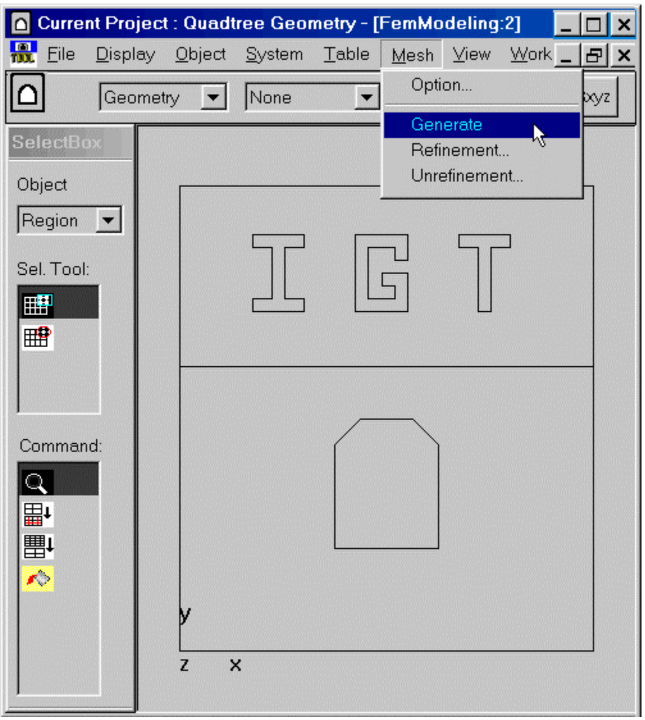


e) Zone resource form for material sets f) Zone resource form for material objects

Fig. 33 Creation of a zone attribute object (part II)

5.3.3 Meshing

It has been shown (c.f. section 4.3.2), that IMAGINE relies on two different geometric representations: a quadtree spatial subdivision algorithm, and a superelement representation.



For both cases the meshing process is applied to the geometric model by menu option *Mesh* (Fig. 34). For this figure a quadtree representation has been chosen, which supports a fully automatic mesh generation. Without specifying any special options, i.e. for a default set, the resulting mesh is displayed in Fig. 35. More than 300 finite elements have been created, some triangles and mostly quadrilaterals.

Fig. 34 Meshing process

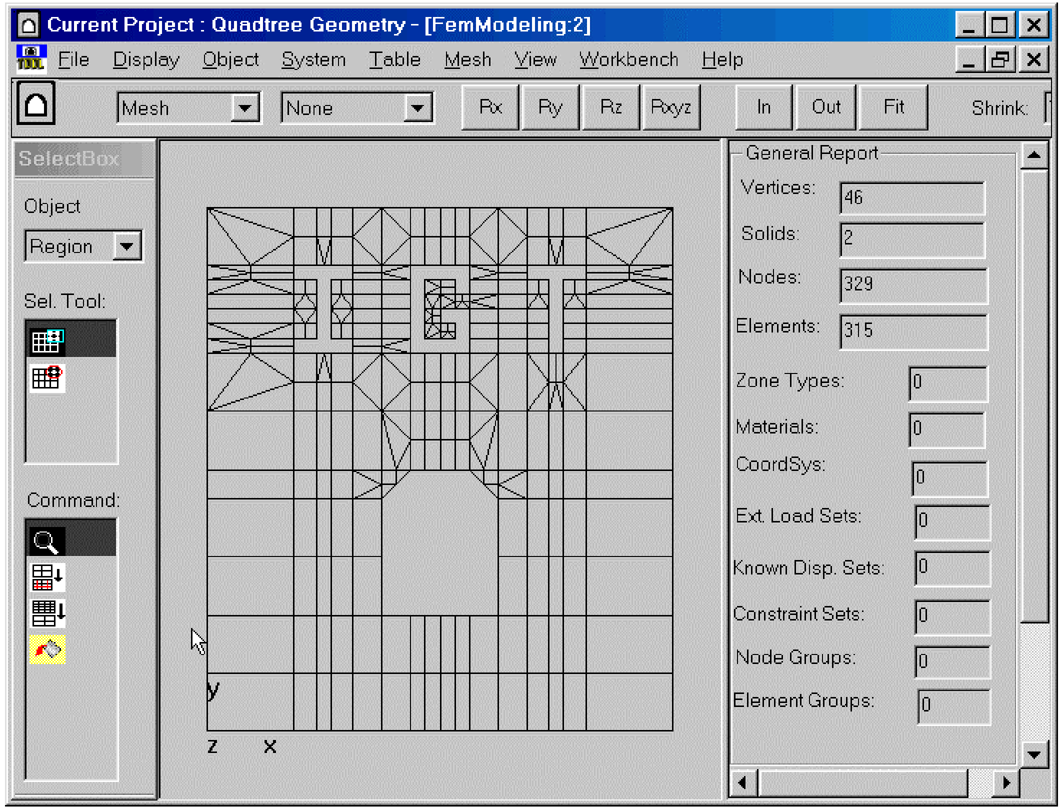


Fig. 35   Coarse mesh

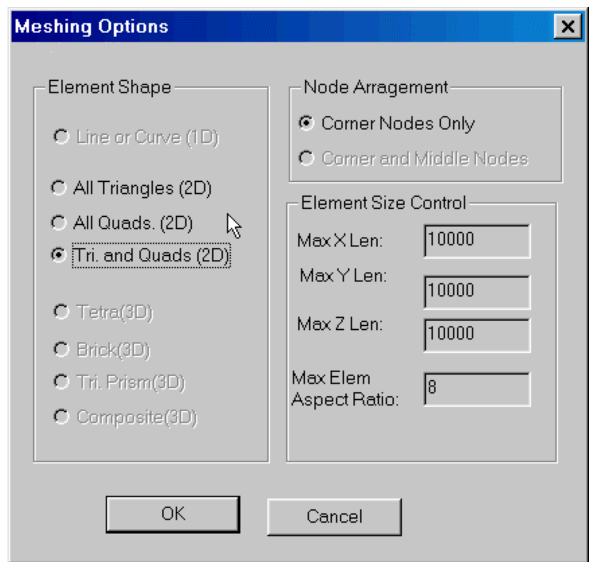
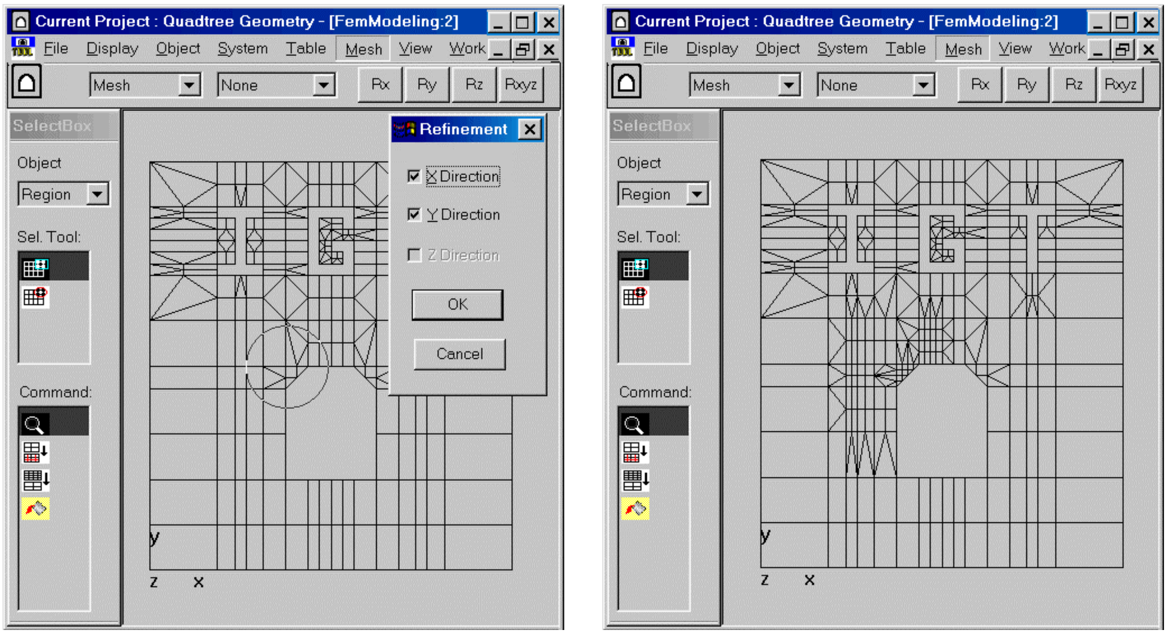


Fig. 36   Meshing options

In Fig. 36 the default meshing options which have implicitly been used are displayed.
For this example the defining parameter was the possibility to create triangles and quadrilaterals. The maximum element size was been decisive.

If, with these settings, the resulting mesh is too coarse, one could change the settings and remesh the whole geometry. Another option would be to select a limited region and just refine this. Fig. 37a) shows this case. A region near the left part of the roof is selected. To this region the *refine mesh* command is applied. As refinement options refinement in the x and y directions has been chosen.
The resulting refined mesh is displayed in Fig. 37b). It may be seen that the refinement is concentrated in the selected region, but, due to compatibility requirements, it is spread out with decreasing intensity to a bigger area.
In a similar process selected regions can also be unrefined.



a) Mesh refinement: region and options

b) Refined mesh

Fig. 37 Mesh refining process

In the above examples the geometric model was based on a quadtree subdivision. The refinement process for a superelement based geometry is less automatic, but allows more controlled refinement in delicate zones. Because there are more options available, they are displayed in the *Form Frame* (c.f. Fig. 38). Each zone which should be refined must be selected and individual refinement options may be assigned. E.g., for the selected zone 19 a local coordinate system R,S is displayed. One could now require subdivision into 3 elements in this zone in the R direction, and into 2 elements in the S direction (a value for *Bias* would divide the zone in an exponential manner). All other selected zones should be divided into 2 elements in each direction (this default could also be changed).

Fig. 38 displays the resulting refined mesh. As required, the zone at the invert is subdivided into 3 elements (in R direction), the rest into 2. It may be seen that a subdivision of the selected zones also causes other zones to be subdivided. These compatibility requirements are automatically fulfilled by the program.
If, e.g., the zone at the invert should be divided into 3 elements in S direction, then also the neighboring zone is divided into 3 elements, and so on.

Some practical consequences for the two different geometric representations will be discussed in 6.3 "Solid model versus superelements".

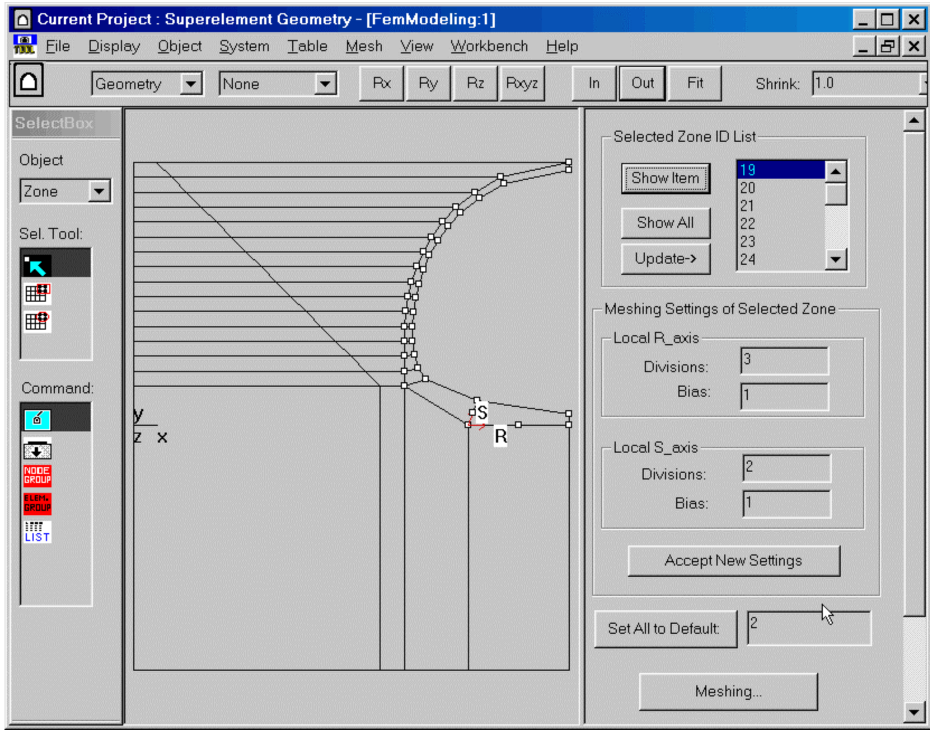


Fig. 38 Mesh refining options for superelements

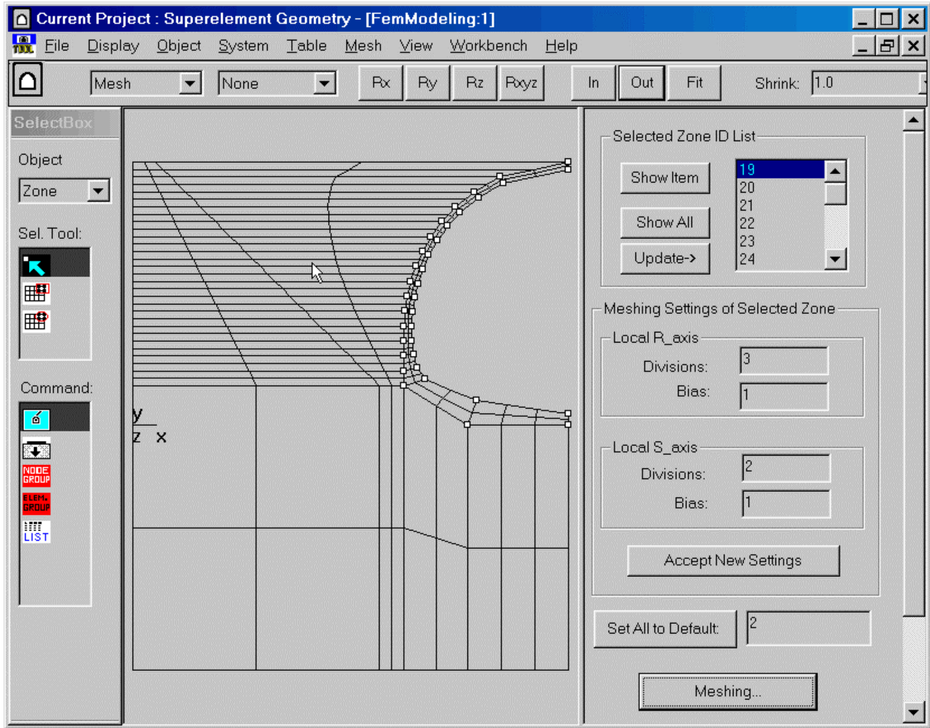


Fig. 39 Refined superelement mesh

5.3.4 Conclusions

Starting from the geometric model of an engineering project the *Fem Modeling Workbench* allows one to define all the necessary resources for an FE computation, including the mesh. It is worth remembering that all resources are defined at the project level but not at the FE level. The meshing process itself occurs completely independently of these resources.

The advantages of this architecture are twofold: simplified input and flexible analysis management. Because assignment of resources at the FE level occurs on the fly during the analysis itself, both project resources and mesh characteristics may be changed at any time.

5.4 Fem Task Workbench

5.4.1 Overview

Given a fully defined geometric profile and resource database, an FE analysis may be carried out. Instead of a hardcoded sequential analysis procedure, IMAGINE relies on a dynamic environment in which the user may define his or her own analysis scheme. The underlying concept with the **FemAnalysis** class hierarchy is described in section 4.3.4. Here the design of the user interface is presented.

IMAGINE adopts an Analysis-Task-Command object model to provide a robust task control engine and a dynamic environment. A **FemAnalysis** object is the control center for an actual FE analysis. More than one **FemAnalysis** objects may be created. This allows one to investigate various scenarios. A **FemAnalysis** object contains one or more **FemTask** objects (e.g. *Apply Loads*). Each task may be understood as a container which again contains some **FemCommand** objects. In the end these objects are responsible for executing some actions. Every **FemCommand** object has its own skill and scope. A set of architectural **FemCommand** classes has been defined for common actions that could occur in an analysis, such as manipulations of geometric objects, load objects, constraint objects and computing objects.

To facilitate a graphic interface in IMAGINE's Analysis-Task-Command object model, the task workbench *Fem Task Workbench* has been designed and implemented. It is identical to *Fem Modeling Workbench* in terms of windows design, except that the *Form Frame* now hosts the task manager form and various task and command forms, respectively.

5.4.2 Task manager

The interface to task management closely resembles the interface of the resource database of Fig. 28. There at the top the available resource types have been listed, followed below by the currently defined sets (containers) for each type, and at the bottom by all objects for the current set.
The main form of the task manager Fig. 40 displays at the top the defined analysis cases, followed below by the currently defined task objects (container) for each analysis. Because each task may be composed of a variety of command objects, a separate form may be activated for them by choosing the button *Edit* (c.f. section 5.4.3). At the bottom of the form, several buttons allow one to control and run the individual tasks or the whole analysis.

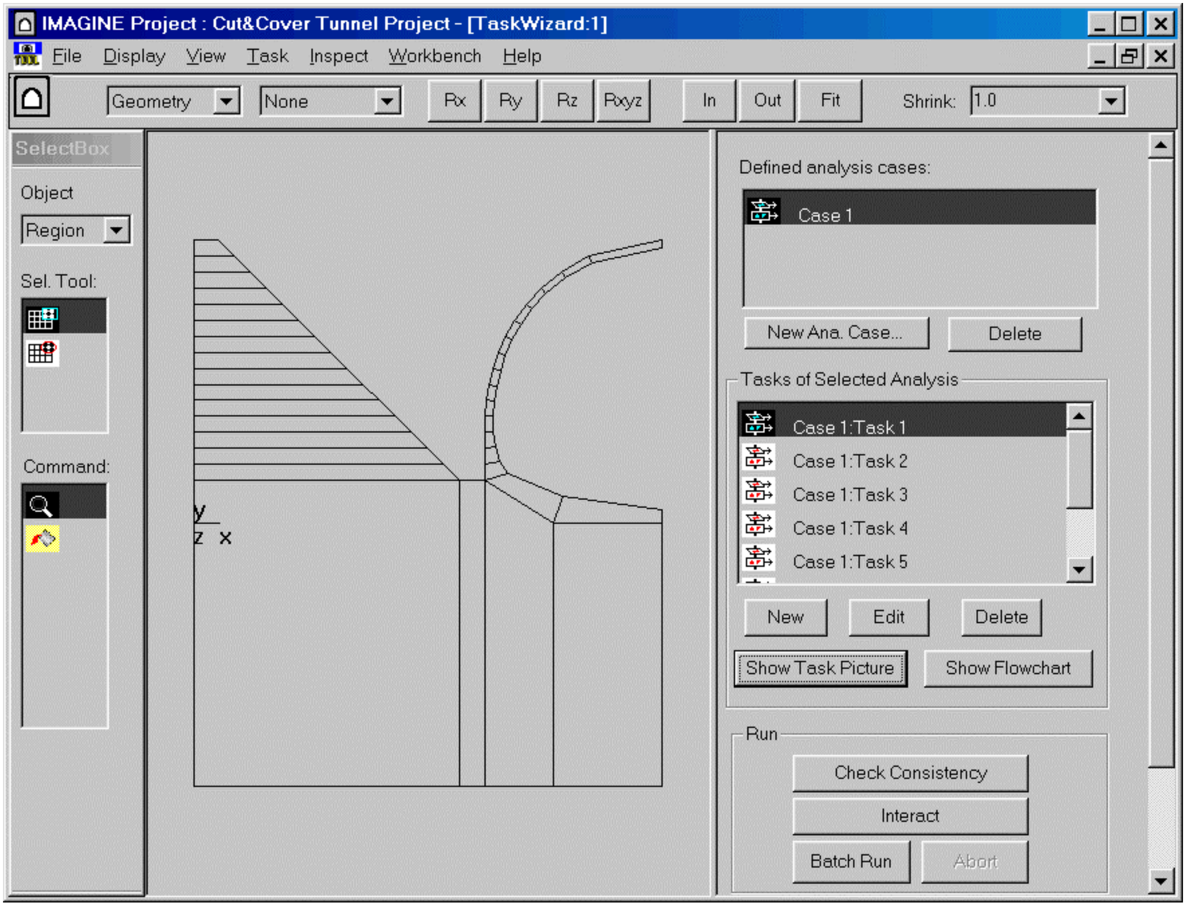
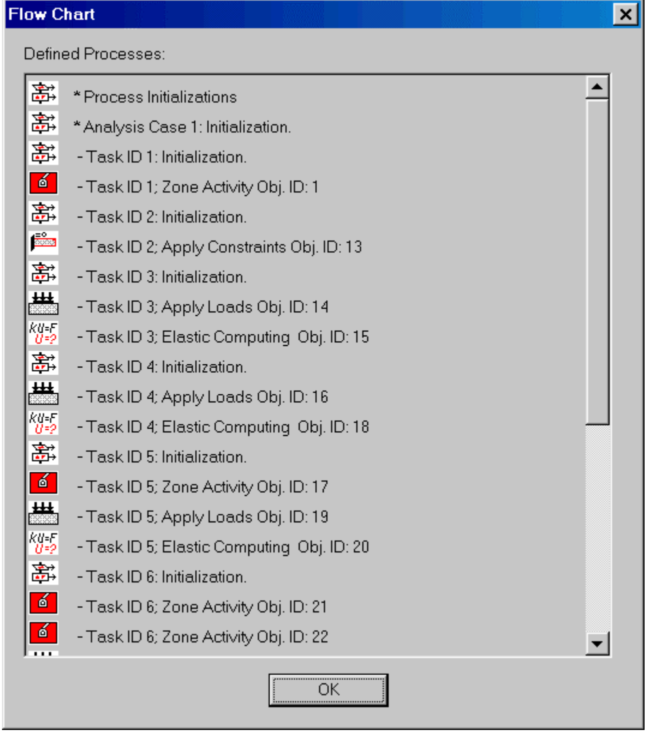


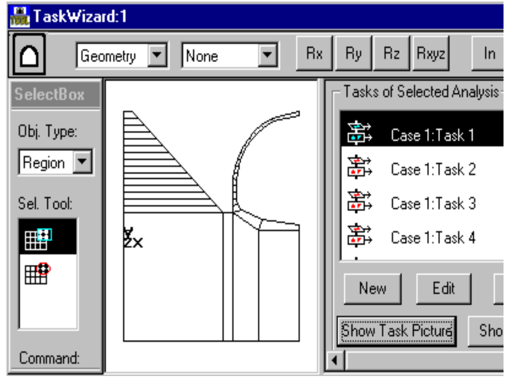
Fig. 40 Interface to the task manager

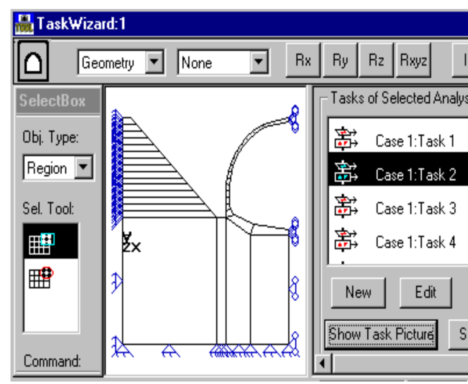


To get a better overview of the individual tasks, some buttons in the task group box provide additional information. E.g. choosing *Show Flowchart* displays the sequence in which the individual commands of each task are executed (Fig. 41).

Further, the button *Show Task Picture* visualizes the geometry and the active resources for each task (Fig. 42).

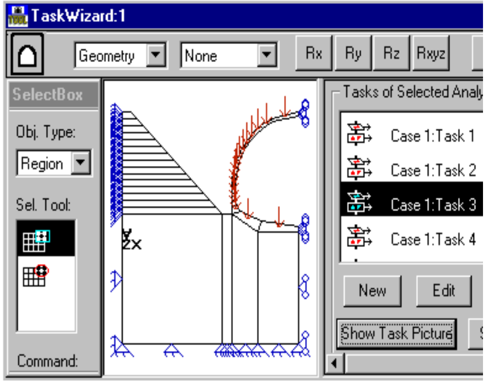
Fig. 41 Flowchart of individual tasks and their embedded commands

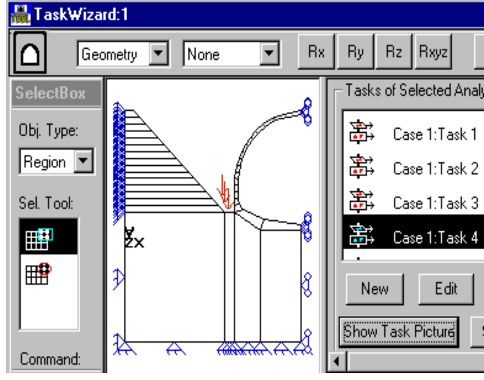




a): Task 1: inactivate "Cover" zones

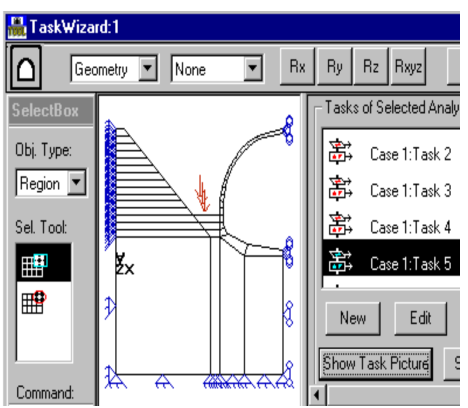
b): Task 2: apply constraints

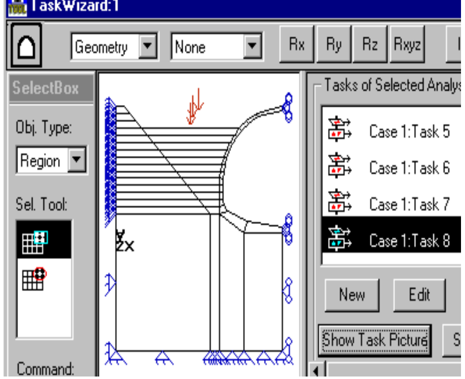




c): Task 3: apply tunnel gravity load, then compute

d): Task 4: apply gravity load of 1st backfill stage, then compute





e): Task 5: 1st backfill stage finished, apply gravity load of 2nd stage, then compute

f): Task 8: apply gravity load of last backfill stage, then compute

Fig. 42 *Show Task Pictures* of some tasks

At the bottom of the form in Fig. 40, several buttons allow one to control the actual execution. Whereas *Batch Run* executes the whole computation without interruption, with *Interact* it is possible to start, stop and resume the execution at the granularity of a command object (Fig. 43). This is especially useful because after each step the current results may be inspected.

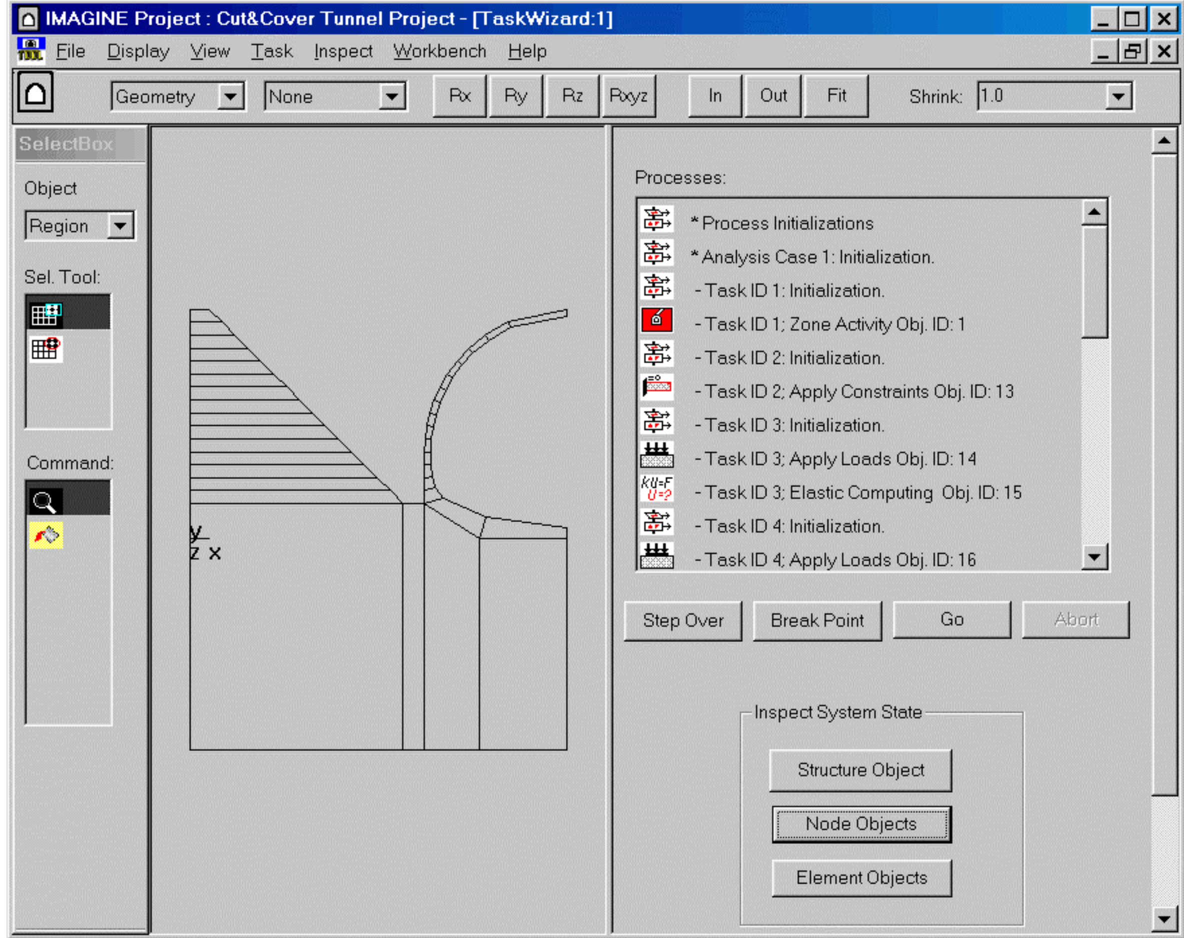


Fig. 43 Interactive execution of individual tasks and commands

5.4.3 *Task objects*

As outlined above, each task may be composed of a variety of command objects. The interface for specifying these objects, the task form, is called when editing or creating a task in the task manager. As an example, for Task 5 of Fig. 42e) the corresponding task form is shown in Fig. 44. At the top, the title and ID of the current task object is listed, and at the bottom the currently applied command objects: some zones are activated, a load is applied and then a computation is carried out. The detailed actions could be checked by pressing *Edit* for a specific command object. However it may be suspected from the model in the *View Frame*, that the zones activated are those of the 1st backfilling stage, and that the loads are those of the 2nd backfilling stage. The command objects are listed in the order of their creation which is also the order of execution.

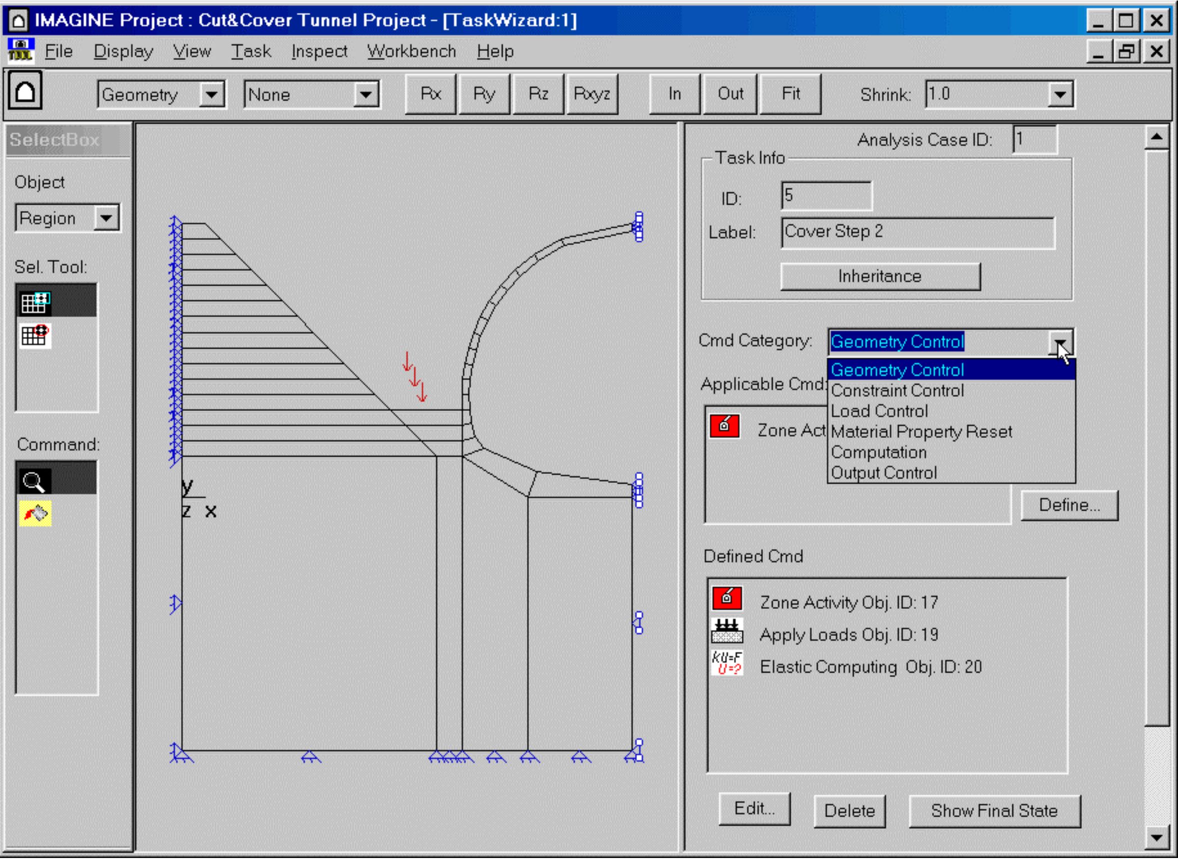


Fig. 44 Task form

For a better overview, the available command classes have been grouped into various categories as shown in the drop-down box in the middle of Fig. 44:

- *Geometry Control*: for specifying zone activities such as activating/inactivating individual zones.
- *Constraint Control*: for applying or removing constraint resource objects (e.g. supports).
- *Load Control*: for applying load resource objects.
- *Material Property Reset*: for changing material properties.
- *Computing*: for controlling computation and update options.
- *Output Control*: for specifying which data should be output in which objects (e.g. displacements in a specified **NodeGroup** object).

For each command category, the applicable commands are listed, which can be defined and assigned to the current task by pressing button *Define*. For each command a corresponding command form is provided.

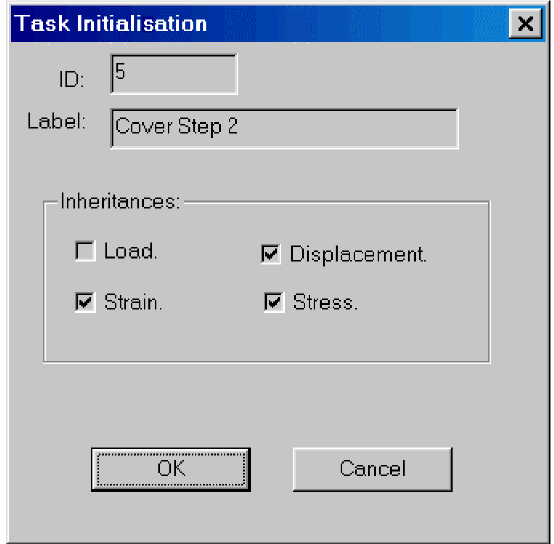


Fig. 45 Task Initialization

The only button of Fig. 44 not yet mentioned is *Inheritance*. This refers to the initial state at the beginning of a task. It is possible to inherit the current state of load, deformation, strain and stress.

Other states not listed in the initialization dialog are always inherited from the previous task, such as the geometry and the constraints. However these may be changed as part of the task by applying the corresponding commands.

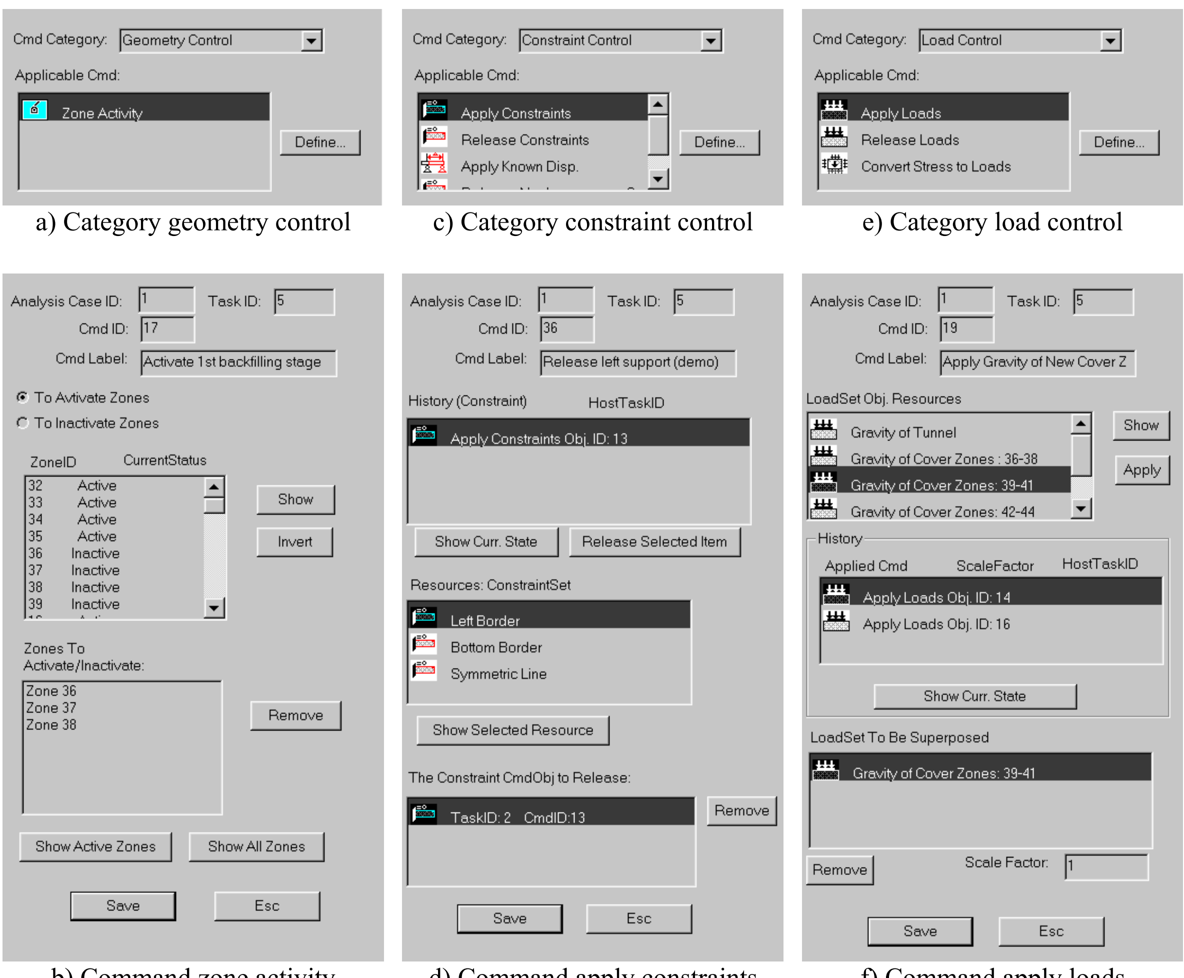
5.4.4 Command objects

In Fig. 46 and Fig. 47 for each command category an example form to define one applicable command object is presented. However it should be remembered that a command category may include several applicable commands, each one having its own form.

Zone Activity command (Fig. 46a & b): This form serves to activate or inactivate individual zones. To make selection easier the zones and their current state may be displayed according to various criteria (for space reasons the corresponding views are not shown here).
The current example still shows task 5 of the 2nd backfilling stage (c.f. Fig. 44). For this stage the three zones 36, 37 and 38 of the previous backfilling stage are activated.

Apply Constraints command (Fig. 46c & d): here the support conditions may be applied. The corresponding resources have been defined earlier in the *Fem Modeling Workbench* (c.f. Fig. 32b).
For the current example of task 5 they have been applied already as part of task 2, i.e. they are inherited from there and must not be applied again.

Apply Loads command (Fig. 46e & f): as the name implies, load resources are applied by this command. For a better overview, all defined load resources are listed in the form, and separately also those which have already been applied in previous steps. If appropriate the same resources could applied, i.e. superimposed, even more than once.
For the example of task 5 the load objects 14 (weight of tunnel lining) and 16 (gravity of 1st stage) have already been applied. Now, for the 2nd backfilling stage, the gravity forces of this layer, i.e. of zones 39 – 41, are applied.



a) Category geometry control
c) Category constraint control
e) Category load control

b) Command zone activity
d) Command apply constraints
f) Command apply loads

Fig. 46 Command categories and examples of command objects (part I)

A special command of the category *Load Control* is *Convert Stresses to Loads*. This command allows one to specify element groups in which the current state of stress should be converted to loads and applied to corresponding nodes. In this way arbitrary excavation sequences may be taken into account.

Material Property Reset command (Fig. 47a & b): if during an analysis the material properties vary, they may be changed by this command. However for consistent usage the responsibility lies with the user.

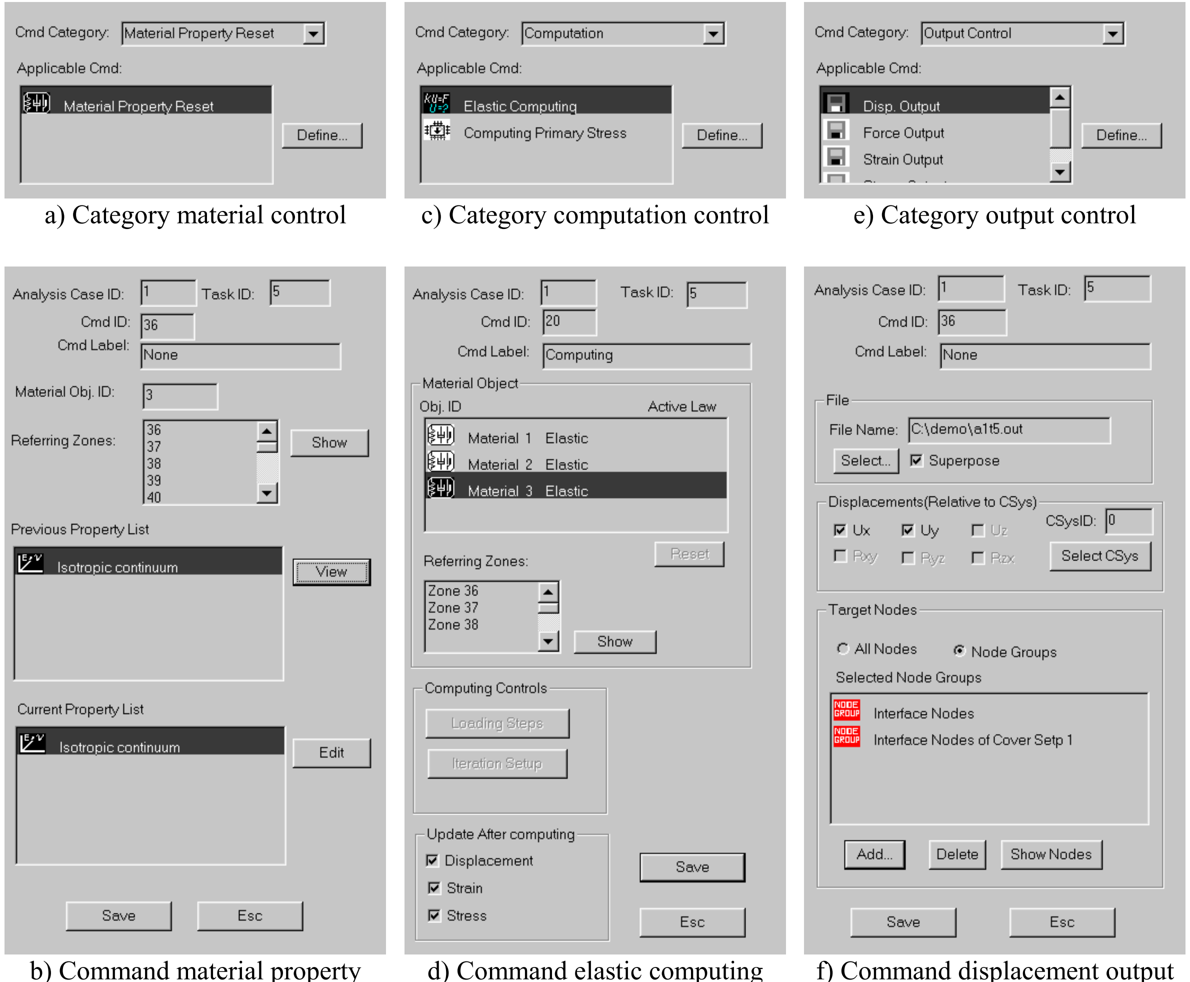


Fig. 47 Command categories and examples of command objects (part II)

Elastic Computation command (Fig. 47c & d): the main aim of an analysis is to execute a computation, even if it is considered here by just one out of many command objects. In the form the currently active material laws and the corresponding zones are listed simply as a help for the user. The laws themselves have been defined and assigned to the zones previously (c.f. Fig. 33). However, if several laws have been defined for a material, individual ones could be inactivated here.
A special command of the category *Computation* is *Computing Primary Stresses*. This command allows to assign a state of stress defined here in an analytical way to selectable element groups.

Displacement Output command (Fig. 47e & f): all commands of category *Output Control* serve to define which field variables acting in which objects (e.g. Gauss points of elements) should be assembled and written to an external file.

As outlined in 3.8 "Postprocessing", this file may be interpreted by 3rd party software, which is responsible for an adequate representation of the results.

It may be interesting to see, that as far as the implementation is concerned all command forms are derived from just one class called **CFemTaskForm** (Fig. 48), which is responsible for the whole windows management. As outlined above, the task form is called when editing or creating a task in the task manager. The individual command forms may then just concentrate on displaying the domain of their limited concerns.

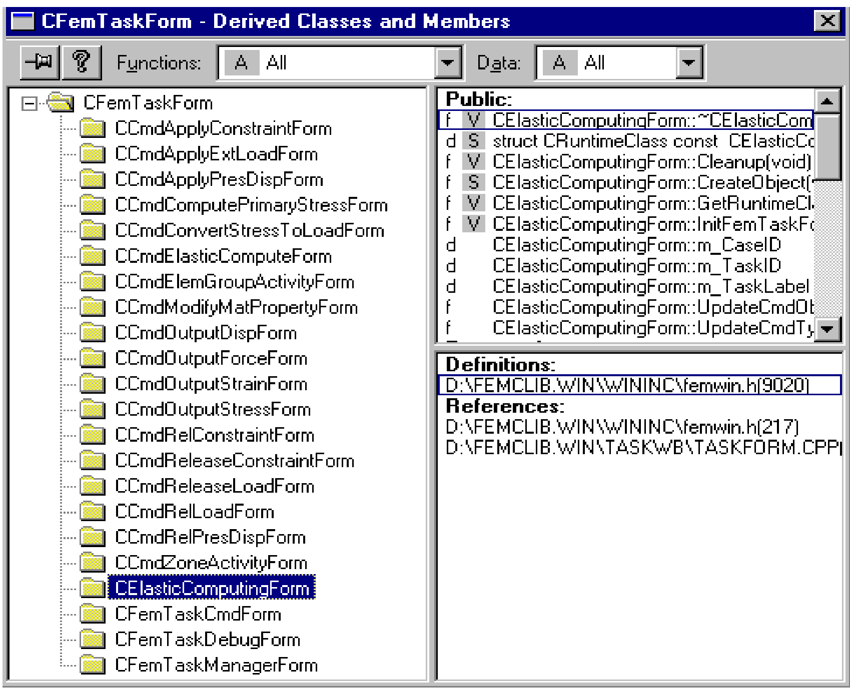


Fig. 48 Class hierarchy of command form classes

5.4.5 Conclusions

The *Fem Modeling Workbench* is used to define all necessary resources at the project level. The *Fem Task Workbench* allows one to assign these resources to computational tasks and dispatch them for execution.

The object centric paradigm of IMAGINE is also continued for the Analysis-Task-Command object model and its user interface the *Fem Task Workbench*. This architecture leads to a very flexible analysis management. The user is practically free to define and assemble tasks. Thanks to the favored non-anticipation of the OOP concept, he or she does not have to care, from a syntactical point of view, e.g. about the sequence in which individual commands may be assigned. Each command object is an independent entity which leaves the system behind in a well defined state. It should be noted that this does not liberate the user from planning the whole analysis carefully. The workbenches provide a powerful means for modeling and investigation, but they do not show what to investigate.

6 Example

6.1 Introduction

To illustrate an application of IMAGINE and its user interface with its object-centric task model the example of a deeply located tunnel may serve (Fig. 49). This example has been extensively discussed by Fritz (1984). Due to its symmetry it may be modeled by a sector of any degree. To illustrate the meshing features a sector of 90° will be chosen.

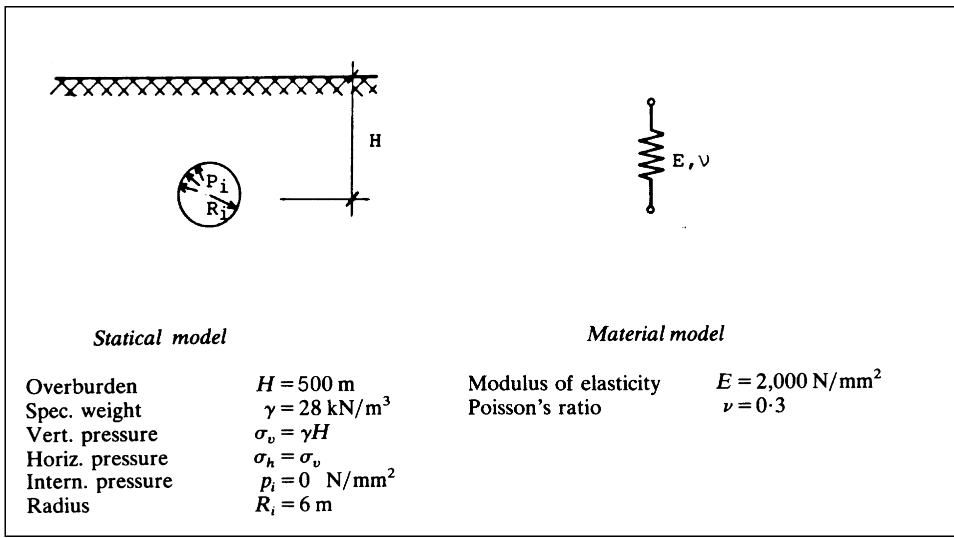


Fig. 49 Model of a deeply located tunnel

6.2 Sector without lining

When starting IMAGINE one is prompted to choose the workbench where one would like to work at the beginning (Fig. 50).

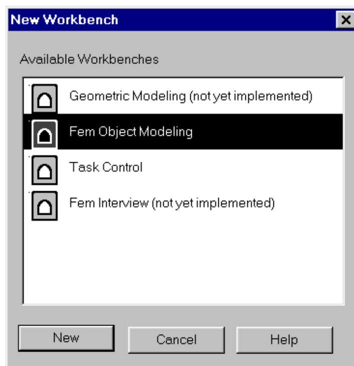


Fig. 50 Available workbenches

The *Fem Modeling Workbench* serves to define all needed resources together with their properties. It is usually chosen first. The *Fem Task Workbench* will be loaded afterwards to define and execute all tasks of the analysis. The other two workbenches serve basically for pre- and postprocessing. At the moment they are not yet implemented. They may be substituted by third party software.
Clicking on *New* leads to the screen of Fig. 51.

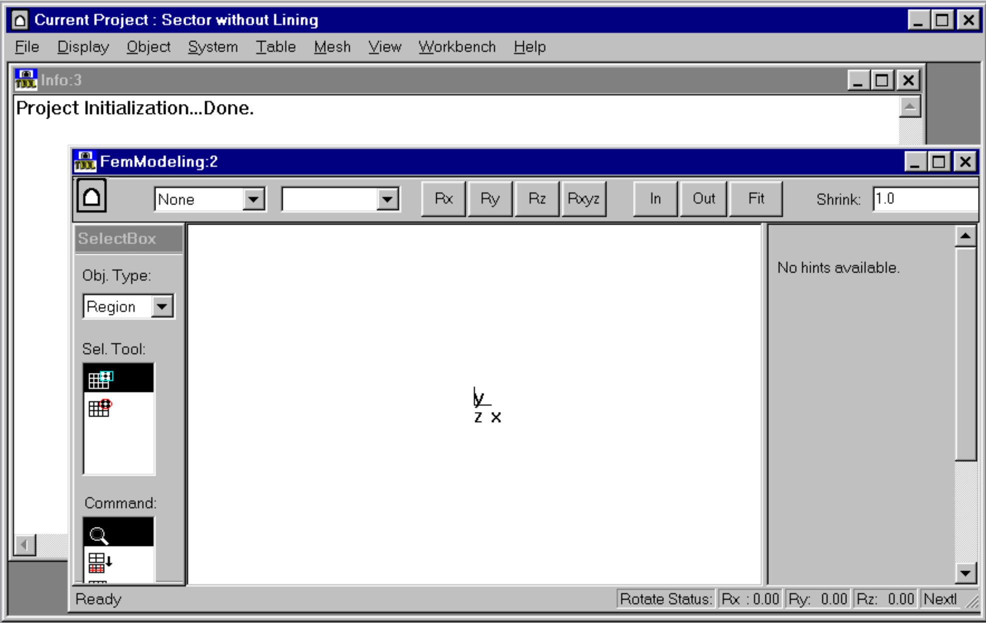
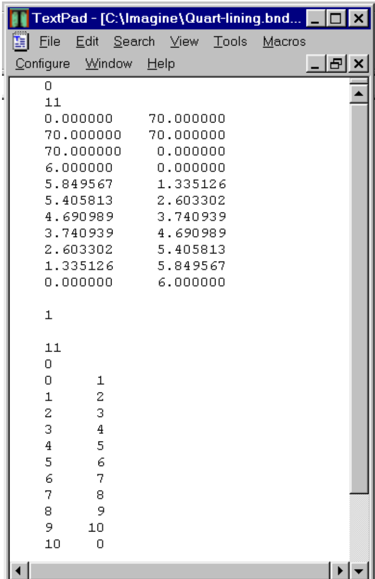


Fig. 51 User Interface of IMAGINE

Two main windows may be recognized. The *Info* window in the background acts as a sort of log book. The *Fem Modeling* window in the foreground represents the actual workbench. To be able to work in it one has to import a geometric model (in the form of a solid model, not an FE mesh, c.f. 4.3.2 "Geometric modeling"). For this example the geometric model is very simple (Fig. 53). It has been prepared with the program FEMAP [http://www.entsoft.com/] and has been imported in the form of an ASCII file (Fig. 52), with menu option *File / Import Geometry File*.


TextPad - [C:\Imagine\Quart-lining.bnd...
File Edit Search View Tools Macros
Configure Window Help

```
0
11
0.000000    70.000000
70.000000   70.000000
70.000000    0.000000
6.000000     0.000000
5.849567     1.335126
5.405813     2.603302
4.690989     3.740939
3.740939     4.690989
2.603302     5.405813
1.335126     5.849567
0.000000     6.000000

1

11
0
0     1
1     2
2     3
3     4
4     5
5     6
6     7
7     8
8     9
9     10
10    0
```

The structuring of the input data is very simple and lucid. The first line is a code which is 0 if the geometry is defined as a solid model, or 1 if it is defined with superelements. The next line lists the number of vertices, followed by their coordinates. Then 1 surface is defined which is described by 11 edges, followed by a reserved code 0 and the topology of the edges, i.e. the numbers of the vertices connecting the edges.
The numbers of the vertices are defined according to their input sequence, starting with 0.

Fig. 52 Input data of solid model

The resulting geometry is displayed in the workbench of Fig. 53: a rectangle of 70 m length, with the excavation center at its lower left corner

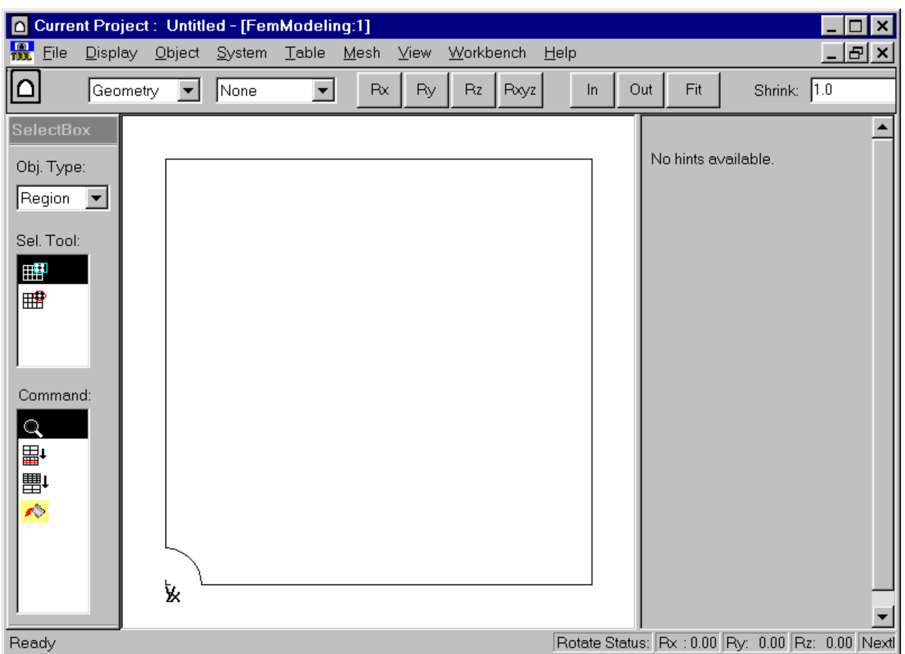


Fig. 53 Fem Modeling Workbench

Three principal frames may be distinguished: the frame on the right is used as an editor in which forms are displayed which may be filled out to specify required data. In the middle the geometry is displayed together with varying graphical information, e.g. the mesh, vectors indicating forces, icons for supports etc. The frame on the left contains the toolboxes which facilitate a working procedure which is in agreement with the object-oriented paradigm. With the drop down box *Object Type* at the top one specifies the object's type, e.g. a vertex, a curve or a surface. According to this type the toolbox *Select Tool* allows one to define how the objects should be selected (with the mouse in the middle frame), e.g. with a rubberband rectangle. In the *Command* box the commands or actions may be chosen which should be applied to the selected objects, e.g. apply a load.

Let's work through the example, how to assign the material properties to the geometric model. To do this one specifies the type of object (*Zone)* in the *Object Type* box at the top (Fig. 54). Then one chooses the selection tool *Rectangle*, and with the mouse a box is drawn around the whole model. The vertices which define the selected zone are marked with empty dots. Because the geometric model consists of just one surface, this surface is regarded as the only zone available. Now the command is specified which should be applied to this zone. Four icons symbolize the possible commands:

- assign a material to the zone,
- apply a distributed load,
- NODE GROUP define a node group which comprises the nodes of the selected zone,
- ELEM. GROUP define an element group which comprises the elements of the selected zone,
- LIST define a list of the selected zones.

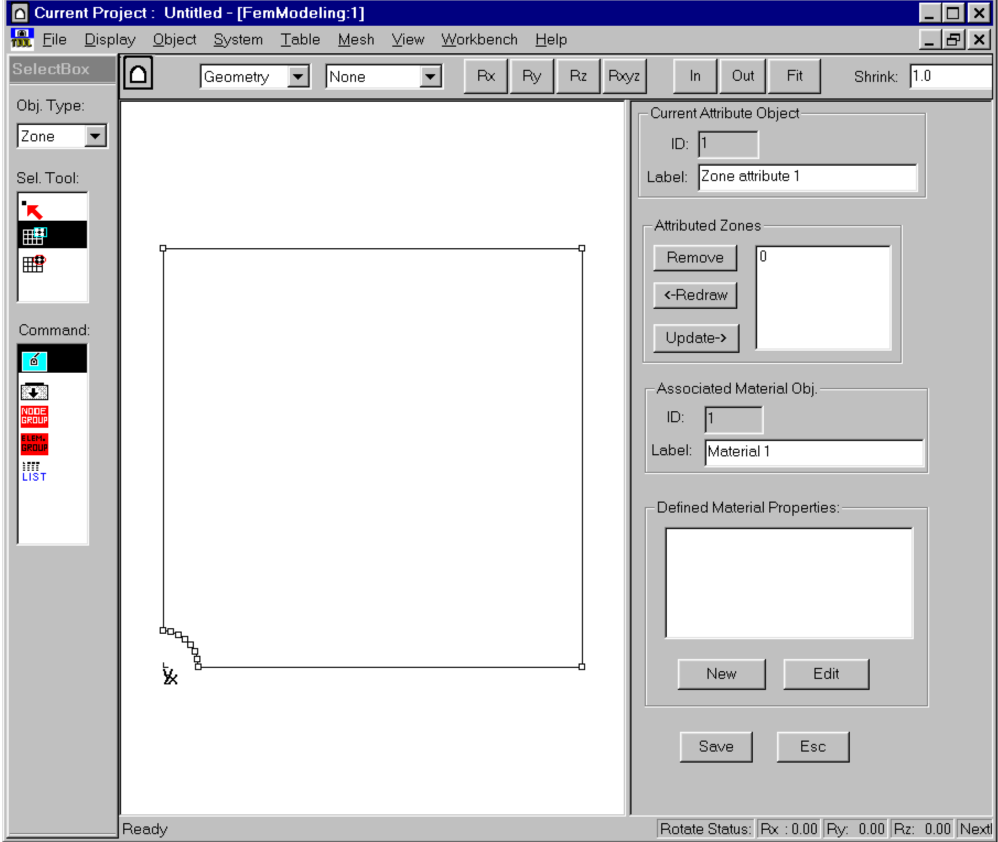


Fig. 54 Assigning material properties to a zone

Clicking on the first icon displays the editor frame at the right hand side in Fig. 54, where the corresponding properties of the object may be defined. Notably missing are material properties, which will therefore be defined now. For this the *New* button is clicked which leads to two dialog boxes where the required data may be input (Fig. 55 and Fig. 56):

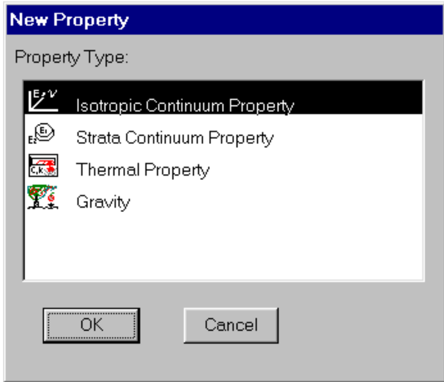


Fig. 55 Choosing the material type

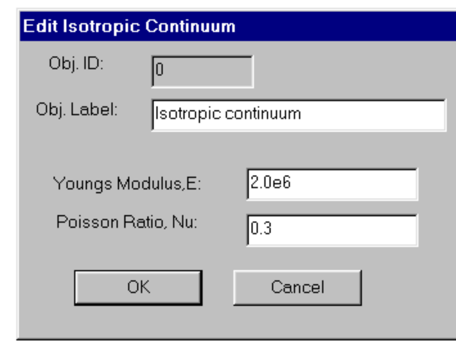


Fig. 56 Defining the material properties

For inspecting the results at the end of the computation, data are often needed in some or all elements and nodes. Therefore already here both an element group and a node group are defined which comprise all items. To do this for the same object type *Zone* the corresponding commands are executed. After saving these objects, in a similar way the support conditions and the forces at the excavation boundary are defined. For this the object type *Curve* is chosen, the corresponding curves are selected and the commands are applied.
Up till now all commands have been applied to geometric objects at the level of the solid model, i.e. independently of the FE mesh. The last step before proceeding to the *Fem Task Workbench*, where the analysis is defined, is to define the mesh. This may be done via the menu option *Mesh / Generate*, leading immediately to the mesh of Fig. 57. This mesh has automatically been generated with the algorithm mentioned in 4.3.2 Geometric modeling. Further discussion of this algorithm follows in the next section. The mesh could easily be refined by clicking the corresponding command icon, but for the sake of simplicity in this example it is accepted as displayed below.

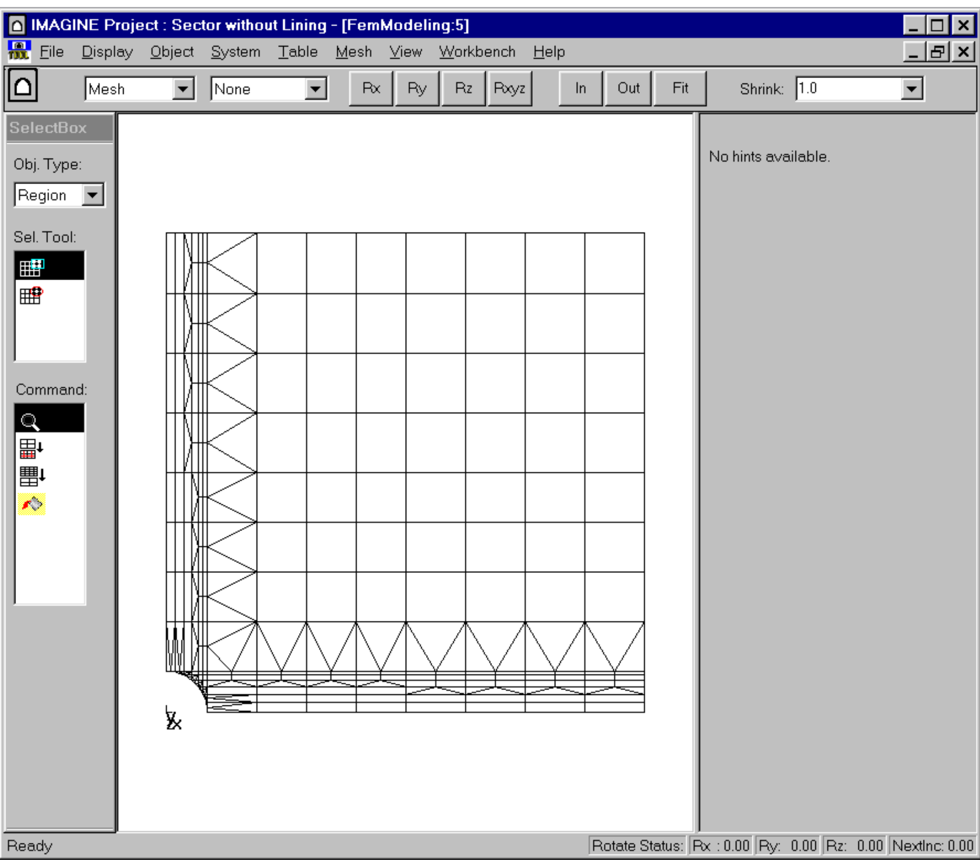


Fig. 57 Automatically generated coarse mesh

At this point the physical model has been completely defined. What is missing is the definition of the analysis, or more specifically its individual tasks. For this one opens a task workbench via the menu options *Workbench / New / Task Control* and the corresponding editor in the right frame via *Task / Taskmanager*. There a new analysis and a first task is defined.

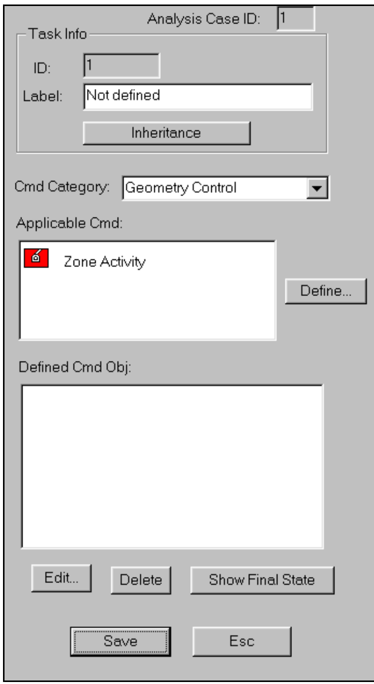


Fig. 58 Task editor

Fig. 58 shows the task editor where specific commands may be assigned to a task. Thus an important field in this editor is the drop down box *Cmd Category* for specifying the command category. According to the category chosen the applicable commands appear in the box below, where they may be chosen by a mouse click. The most important command categories are displayed in Fig. 59.

The first task for the current example is to determine the primary state of stress, the second to compute the redistribution of stresses and the corresponding displacements due to the excavation. Therefore for the first task one needs to define the command categories *Geometry Control*, where the zone defined above is activated, *Constraint Control*, where all defined supports are activated, and *Computation*, where *Computing Primary Stress* is chosen. Input for the first two categories is straightforward, the last one is somewhat more complicated and is discussed below.

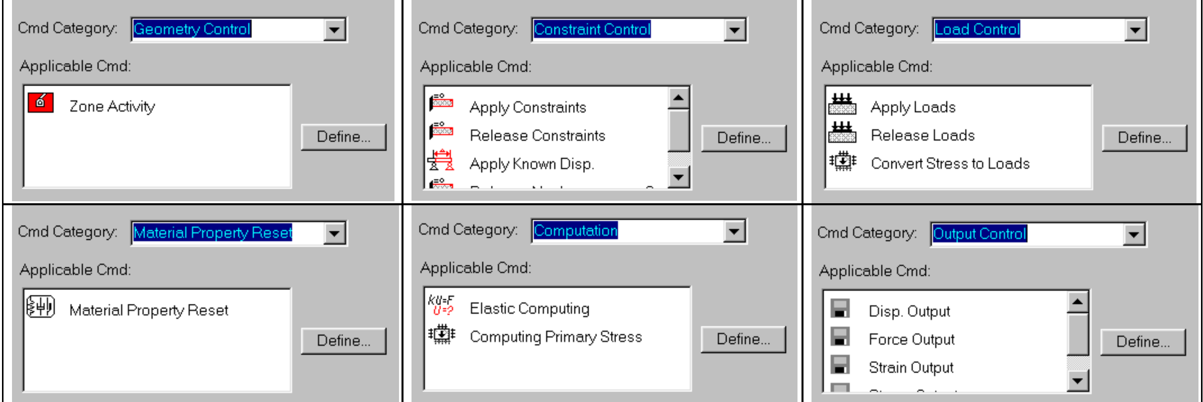


Fig. 59 Task command categories and applicable commands

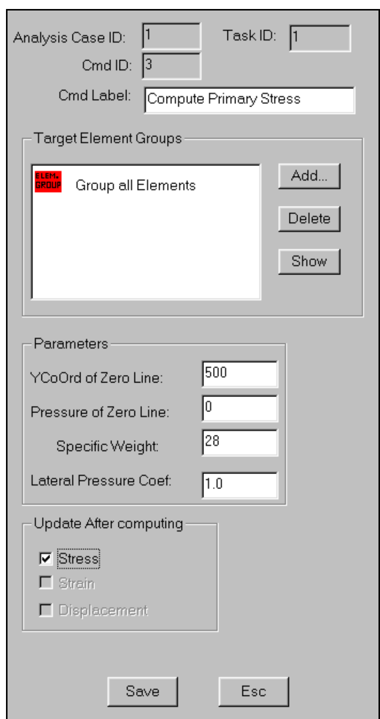


Fig. 60 shows the editor where the task *Computing Primary Stress* may be defined. First one needs to specify for which elements this task holds. For this example one chooses the *Group of all Elements* defined above. In the box below the parameters are defined which characterize the primary state of stress. In Geotechnics it is well known that the primary state of stress depends on many uncontrollable influences, which are usually not known by the engineer. Therefore IMAGINE provides the possibility to define it with a few but important parameters: the overburden, the specific weight, and the coefficient of lateral pressure. The data analytically calculated based on these parameters are then assigned to the finite elements, without actually executing an FE computation.

Fig. 60 Computing primary stresses

For the remaining second task one defines the command categories *Load Control*, where the forces due to excavation at the excavation boundary are activated, once again *Computation*, but this time specifying an elastic computation, and *Output Control*. For the latter displacements in all nodes and stresses in all elements are requested.

The actual analysis may be run interactively by clicking the corresponding option in the main analysis frame. In the process window (right frame in Fig. 61) all defined commands are listed for all tasks which form the current analysis. They may all be executed together or up to a so-called break point which may be set by the user.

During the computation some log information is written to the *Info Window*. All results requested under *Output Control* are automatically written to a file. As outlined above the graphic facilities to display the results have not yet been implemented in IMAGINE. Therefore for this example IMAGINE has been configured to display the results in Tecplot [http://www.amtec.com/]. Just clicking the menu option *Postprocessing* (c.f. Fig. 61) first calls a special conversion program which assembles the data of IMAGINE's results file and converts it to a format supported by Tecplot, and then loads Tecplot (Fig. 62).

When popping up Tecplot automatically displays the mesh of the current example (Fig. 62a). With just a few mouse clicks one can display contour lines (Fig. 62b) or vector diagrams. An additional valuable feature of Tecplot is the possibility to extract values along an arbitrary polygon, e.g. along the x-axis, and to display these values in a new diagram.

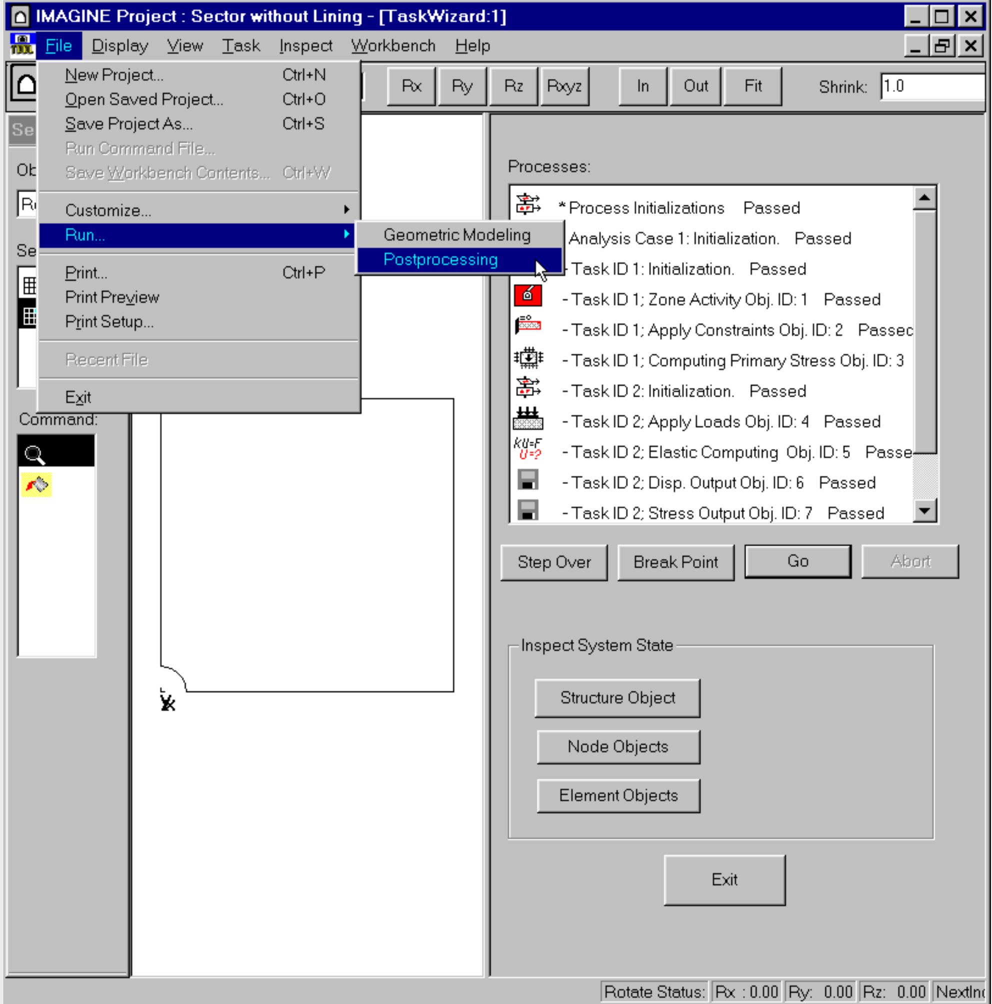
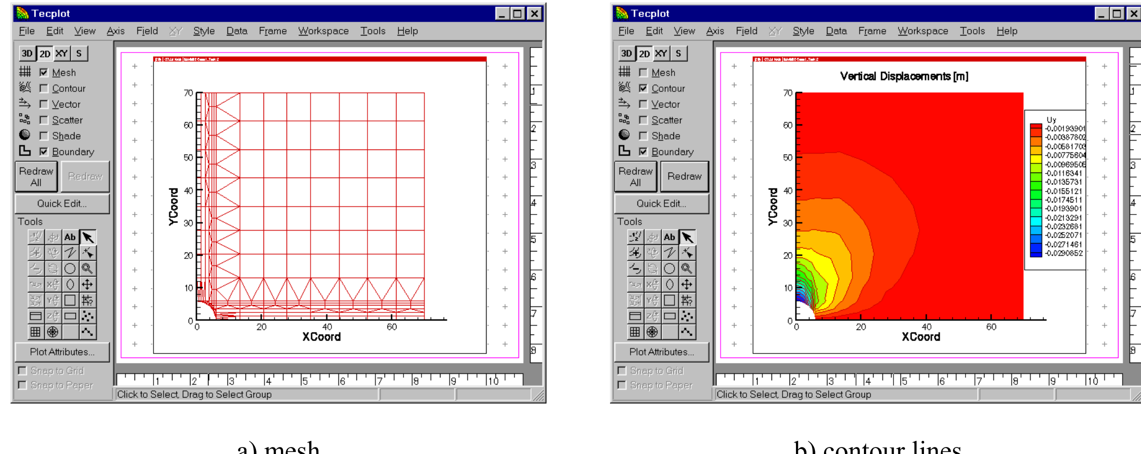


Fig. 61 Process window and postprocessing menu

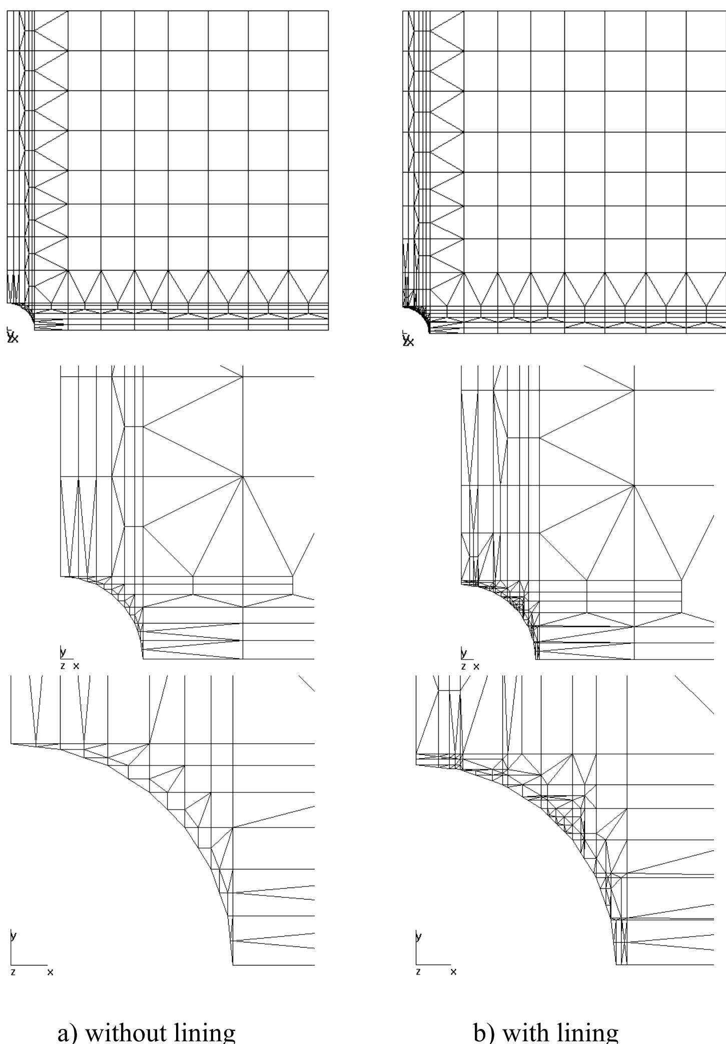


a) mesh b) contour lines

Fig. 62 Tecplot postprocessor

6.3 Solid model versus superelements

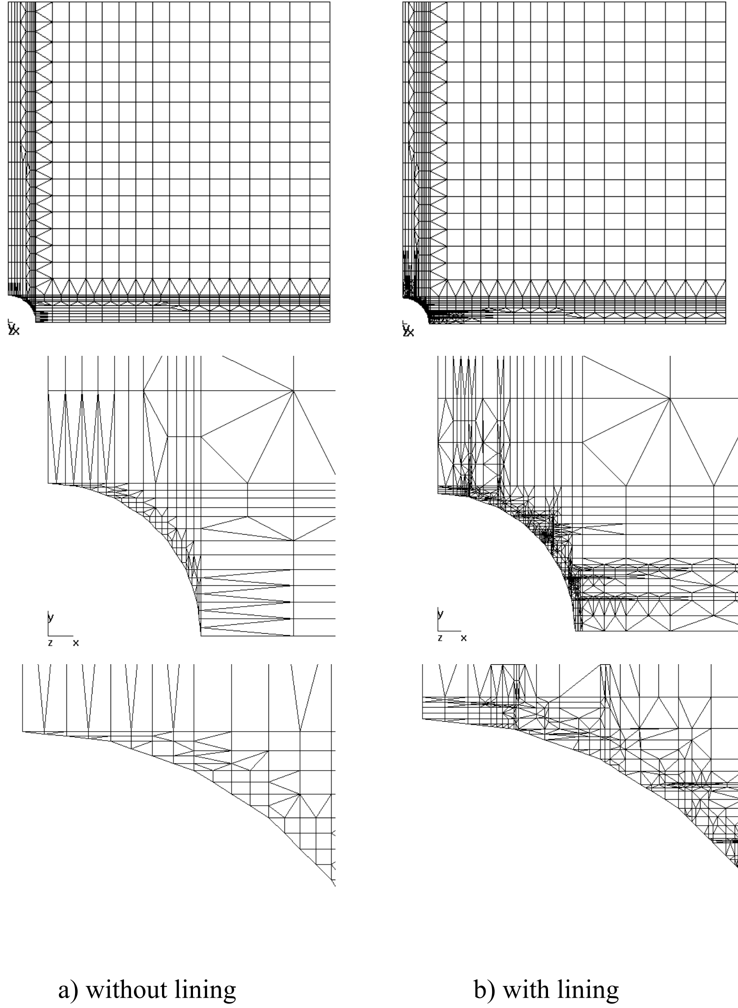
The example outlined above demonstrated the power of the automatic meshing algorithm of IMAGINE. Unfortunately it does not always lead to satisfactory results. For illustration purposes the same geometric model as above is used, but with the addition of a lining of 30 cm thickness. In Fig. 63 the mesh has been automatically generated with default parameters, i.e. without any special measures for improving its quality. On the left side the mesh without a lining is displayed, the geometry on the right side includes a lining. The individual rows show the meshes at various degrees of zooming. One recognizes that the mesh in the vicinity of the excavation surface becomes irregular, especially for case b) with a lining.



a) without lining b) with lining

Fig. 63 Coarse FE mesh created from a solid model

Fig. 64 shows a similar picture but for a refined mesh. Refinement was executed by selecting the initial mesh and clicking *Refine*. It may be recognized that for this case the irregularities in the vicinity of the excavation surface become even more pronounced. The reason is that the mesh generator starts to mesh the lining at the crown with a reasonable subdivision. For the sake of numerical accuracy it subdivides the area using triangles and quadrilaterals, the latter having no obtuse angles. As the lining curves downwards smaller and smaller elements are generated.



a) without lining b) with lining

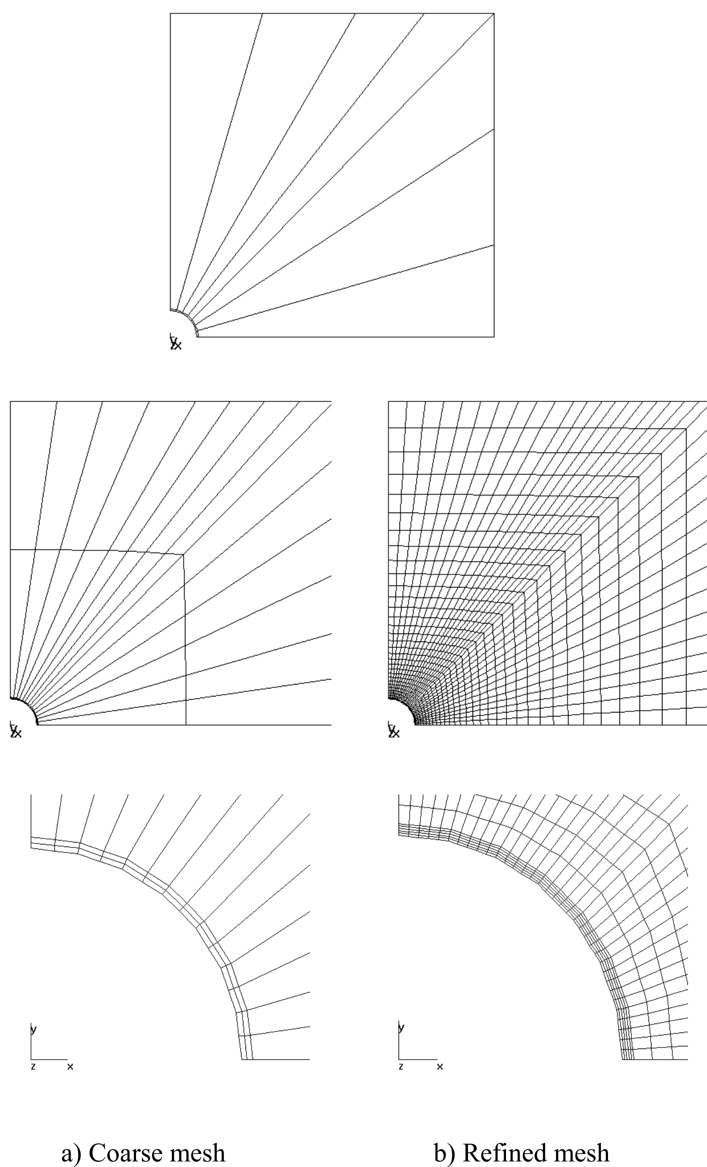
Fig. 64 Refined FE mesh created from a solid model

This phenomenon could be avoided by first generating the mesh for the lining semi-automatically with a regular subdivision, and then automatically for the rest of the geometry. However, a corresponding algorithm is quite demanding and at the moment not implemented.

IMAGINE solves the problem in another way, though with some loss of generality and automation. Instead of specifying the geometry with a general solid model, a 2D area may be subdivided into a number of quadrilaterals, so called superelements. The geometric model at the top of Fig. 65 has been subdivided into seven areas or superelements for the lining, and seven superelements for the rest of the profile. Some third party software such as FEMAP supports the definition of superelements. During the meshing procedure IMAGINE subdivides opposite edges of a superelement into a selectable number of stretches. To guarantee compatibility such subdivisions are propagated to neighboring elements.

Part a) of Fig. 65 shows the resulting mesh having accepted all default parameters. For part b) one superelement of the lining and one of the rest have been assigned a refined subdivision. For the latter, additionally, an exponential subdivision has been specified. In this way a satisfactory mesh may be created.

It may be seen that the meshes based on superelements are much better balanced than their counterparts of Fig. 64 based on solid models.



a) Coarse mesh b) Refined mesh

Fig. 65 FE mesh created with superelements

7 Conclusions

The object-oriented Finite Element framework IMAGINE has been presented which may be used as a robust foundation for building applications in the field of geotechnical engineering. It was shown that the decision to concentrate on geotechnical engineering was correct. Other frameworks stemming from academic or informatics sources usually foresee extendibility to different types of finite elements, or to improved solution procedures. Opposed to that, IMAGINE aims to be extendable in terms of material models, types of physical variables and management of computational tasks.
The object-oriented approach simplifies the task of creating a flexible, extendable and easy-to-maintain program system. However, it is very important to have a well-structured and clearly layered design to exploit it to the full.

Furthermore, it was recognized that there is a great difference between developing a framework just as a proof of the applicability of a specific concept, and providing a framework which should be usable and extendable for engineering practice and for research work. The main aim of the IMAGINE project was to provide a framework in the sense of a numerical infrastructure, on which developers can build to integrate required extensions with a minimum of development time and side effects. This aim of the framework has certainly been fulfilled. It is now ready to develop applications upon it.

However, in agreement with the quotation in the Introduction ("... *now we have gigantic computers, programming has become an equally gigantic problem.*") the demands on the style and the comfort of a program have increased so much, that building such applications is still a considerable work, even with the underlying aid of a framework. Up till now 6½ man years have been invested in the project of IMAGINE. Before a new programmer could efficiently start to work with it he or she would need to study C++ and IMAGINE itself, which would consume between a couple of months up to one year. Integration of new elements, e.g. beams for simulating a lining, would require additional time. This time is necessary not so much for integrating the element itself, but to adapt the corresponding routines for the automatic meshing (c.f. 4.3.2 "Geometric modeling"). Another important task consists in integrating more complex material laws than just the elastic one currently defined.
Thus let us continue as the slightly adapted saying is: Master, the work is finished, when should I start to extend it ?

Appendix 1: From procedural to object-oriented programming

From the beginning of software engineering, the constructive design of the programming language played a central role in improving the ratio between benefit and expenditure. The following summary provides a condensed version of the evolution from procedural to object-oriented programming, thereby enabling an insight into the fundamental principles of OOP. This evolution may be split into five significant steps (Marti, 1988):

- Subprograms,
- Functions,
- Modules,
- Abstract Data Types,
- Object-oriented Programming.

The idea of *subprograms*, as used in the form of Macros in Assembler or GOSUB in Basic, was to prevent duplication of code, and not to increase the level of abstraction. They were not functional entities. Because no parameters could be used, control had to be exerted by external variables.

Functions, e.g. called FUNCTIONs and SUBROUTINEs in FORTRAN, represent functional entities and support parameters for input and output. However, they are still embedded in the global data space (e.g. through COMMONs), and therefore they are error prone to side effects. Their design is based on stepwise refinement (Wirth, 1971), executed in a sequential manner, which is called top-down design.

Modules, as promoted by Modula (Wirth, 1982), introduce information hiding by division in a public interface, containing all external relations, and a hidden implementation part. Modules may contain several functions, i.e. they represent abstract data types with respect to functions. Because Modules are static entities which may not be individually derived for different objects, their data correspond to the sum of all objects, i.e. modules are not abstract data types with respect to data.
To improve reusability it is tried to form families of modules covering a specific task, which means that top-down design is mixed up with bottom-up design.

Abstract Data Types, as introduced by Simula (Dahl and Nygaard, 1966) and used by C++ (Stroustroup, 1998), contain data *and* the associated functions. The technique for this relies on classes, analogously to modules, but which can be instantiated for each object separately. In C++, even operators may be defined as abstract data types (so-called operator overloading). Which class is effectively called is decided by the compiler depending on the types of operators involved. This characteristic is referred to as compile time polymorphism, or early binding.
A limitation of abstract data types is that they are defined independently. If they should be reused or extended, their source is copied and adapted. If one of such similar types is changed, all others must also be updated.

Object-oriented Programming overcomes the above mentioned limitation by supporting hierarchical structuring of abstract data types. This is achieved by inheritance and aggregation.

With the concept of inheritance specializations of a class may be added by deriving subclasses where only the differences must be defined. Derived classes inherit the non-private behavior (member functions) and context (member data) of their base classes. In a similar way aggregation embeds objects or references to objects into a container object. Derivation typically implies a top-down design (passing from the generality to the specialization), aggregation a bottom-up design (passing from simple classes to complex ones).
Objects communicate with each other by calling their member functions, or expressed in OOP words, by sending messages. If a derived class may not satisfy a message it is passed to its base class. If a pointer of one class points to another (derived-) class, the programming language provides mechanisms to define whether a message should be transferred to the base class or the derived class (see below). In this way extendable class hierarchies of logically or technically similar entities may be built.

Because a derived class is more specialized than its base class, all member functions of the base class may also be used for an object of the derived class. This implies that a pointer of a base class may always be assigned an object of a derived class (but not vice versa). In this case it must be defined which member function should be called if it is defined at various hierarchy levels. As default, the class defined by the type of the pointer is activated. However, if a member function is defined as virtual, the class is activated to which the pointer currently points. Because the latter may only be decided at run time, this ability is called runtime polymorphism, or late binding.

Typical for OOP is that projects are not developed sequentially, starting from analysis over design and implementation to testing, but rather iteratively or recursively, i.e. iteratively in parallel over all stages. This means that design and implementation should not be treated separately anymore.
In the life cycle of a project often a broader applicability of a solution is discovered. I.e. useful abstractions are more discovered than invented. The procedure is again a combination between top-down (decomposition) and bottom-up (assembling existing classes).

Appendix 2: Software life cycle

As mentioned above, the life cycle of software viewed in the light of object-oriented programming (OOP) comprises (Berard, 1993)

- Object-oriented requirement Analysis (OOA),
- Object-oriented Design (OOD),
- Object-oriented Programming (OOP),
- Testing, and
- Maintenance.

The definitions and the requirements of these processes may not be listed in a strict and comprehensive manner. However, as guidelines the following rules of thumb may serve.

The *Object-oriented Analysis* (Coad and Yourdon, 1990) defines the external characteristics of the system which are visible to the user and the key abstractions. It provides a model of the systems behavior. It comprises

- describing the whole system,
- requirement specification,
- identification of sources of information (books, people, software etc.),
- identification of candidate objects (frameworks, development kits, classes etc.),
- building models (textual, graphical, executable etc.),
- selecting and creating candidate objects.

The *Object-oriented Design* (Coad and Yourdon, 1991) creates and documents the internal architecture of the system. Classes are designed and their interrelationship and interaction are described:

- identification of objects,
- identification of operations suffered by and required of the objects,
- selecting, creating and verifying objects,
- establishing interfaces of objects.

Object-oriented Programming (Booch, 1994) implements a program as collections of objects. It comprises:

- choosing a programming language (factors of influence are weak or strong types, concurrency, persistence, garbage collection etc.),
- resource allocation,
- release management and version control,
- building the class interfaces,
- implementation.

Testing (Berard, 1993) should be a continuous activity during the whole life cycle. It includes

- debugging,
- demonstrating adherence to external specification,
- identification of singularities,
- creating test suites,
- software quality assurance.

Maintenance (Booch, 1994) is the activity of managing postdelivery evolution. Application of the software by independent users, usually the ultimate goal of each project, may lead to feedback not only with regard to errors but also to improvements and extensions, i.e. to all preceding steps of the whole life cycle, with diminishing probability of occurrence.

Appendix 3: The Document-View Concept of the MFC

The *Document-View Concept* distinguishes between the data of an application, which resides in a class **CDocument**, and the view of it, controlled by class **CView**. Additionally, it relies on the application object, and the frame window (c.f. Fig. 6).

CView is responsible not only for the actual display of the data, but also to take and forward all user interactions which could change the display either directly or by changing the underlying data. **CView** is a child-window of a frame which is never displayed. It exactly fits in the main frame window, it represents the working area of the frame window. If the size of the frame window is changed, so is the size of the view window. However, the view of the data should not be mixed up with their actual display. The display is delegated to **CFrameWnd**, which resides at the same level in the class hierarchy as **CView**, i.e. both are derived from **CWnd**. If one would try to write something directly to the frame window, it would not be displayed, because the frame window is completely covered by the view window. However, **CFrameWnd** detects which view is active and its size, and sends the view the corresponding message to update the display.
The *Document-View Concept* is therefore just a higher level abstraction integrated in the MFC. Also when programming without the *Document-View Concept* all frames are usually derived from **CFrameWnd**, and the application itself is derived from **CWinApp**.

The *Document-View Concept* facilitates program development because it includes many standard tasks of a program, e.g. standard dialog boxes when closing a project or when printing. A further advantage is that it relieves the programmer from organizing the whole information flow between the application object, the document and the view. This is especially true in the case of IMAGINE which relies on the Multiple Document Interface (MDI), which allows displaying several views of a document.

Additionally, the class **CDocTemplate** provides templates for creating new documents and views, e.g. for a sound application, or for a new Imagine project (via menu option *File* / *New*). **CDocTemplate** serves to enable instantiating documents and views whose type is determined at runtime.
For instantiating objects, e.g. documents and views, whose type is determined at runtime, the MFC provides so-called runtime classes. Each class, which is derived from **CObject,** may fill in some member data of **CRuntimeClass**. A member function of **CRuntimeClass** then allows creating objects whose class is determined at runtime only. The MFC provides two macros to fill in the necessary member data: DECLARE_DYNCREATE(CMyClass) must be inserted in the header file, and IMPLEMENT_DYNCREATE(CMyClass, CBaseClass) in the corresponding source file.

Appendix 4: Style guide

Introduction

A lucid programming style is an indispensable prerequisite for maintaining a large program. Yoon (1990) reports that almost 95% of all failed software projects of the U.S. Government Accounting Office can be attributed to impossible maintenance and adaptation to new requirements. Undisciplined programming style is very hard to prevent. However, it is hoped that the OOP paradigm leads also to an improved style, e.g. due to its inherent abstraction possibilities.
To improve the global overview it was aimed to document each file, class and member as outlined below. To improve readability in the small mnemonic names for types and variables are used.

Online documentation

> *The professional software engineer acknowledges the importance of creating certain documents, but never does so (Booch, 1994).*

Blocks of comments are inserted in a routine way at the following three places:

- at the beginning of each class,
- at the beginning of each method,
- at the beginning of each file.

At the beginning of **each class** the following template is introduced, filled out with the necessary information:

```
//************************************************
//class ClassName:              - short description
//     Description:
//     Creation Parameters:
//     Destructor Behavior:
//     Methods:                 - prototype and short description
//     Parent Classes:
//     Child Classes:
//     Friend Classes:
//************************************************
```

It should be noticed that especially the information about the child classes may sometimes not be complete, because subclasses may be derived without changing this information in the baseclass (intentionally or unintentionally).

Similarly at the beginning of **each method** the following template is introduced:

```
//************************************************
//MethodName::ClassName:        - short description
//     Description:
//     Parameters:
//     Class variables:
//     Methods:                 - prototype and short description
//     Files:
//     Returns:
//************************************************
```

Similarly at the beginning of **each file** the following template is introduced:

```
//***********************************************
//FileName:                  -   short description of contents
//
//standard header files
#include directives         //   e.g. <iostream.h> etc.
//class declarations
#include "appdefs.h"        //   forward declarations of all essential
classes
#include directives         //   forward declarations of local classes
//function declarations
#include directives         //   forward declarations of functions
//basic definitions
                             // typedefs's, constants etc.
//local header files
#include directives         //
//***********************************************
```

Naming conventions

Readability in the small is achieved by adhering to some naming conventions, especially the so-called Hungarian Notation (Simonyi and Heller (1991), for a summary see also http://home.jtan.com/~gregleg/hungarian.html or http://support.microsoft.com/support/kb/articles/Q173/7/38.asp). This notation specifies the form of variable names in order to lead to information about their content. Specifically variable names should be prefixed with one or more lowercase characters to indicate their type, and the name itself should start with an uppercase letter, e.g.

Prefix	Meaning	Explanation
ch	char	signed char, 8 bit int
by	BYTE	unsigned char, 8 bit uint
w	WORD	unsigned int, length machine or OS dependent
s	short	16 bit int
us	unsigned short	16 bit uint
n	int	length machine or OS dependent
u	unsigned int	length machine or OS dependent
i	long	32 bit int
ui	unsigned long	32 bit uint
ft	float	32 bit float
dft	double float	64 bit float
b	BOOL	unsigned char, 8 bit uint
sz	zero terminated string	
s	string	
C	class	
p	pointer	
r	reference	
a	actual value	
c	int or long	counter
f	BOOL	flag
x,y,z	float	coordinates
d		difference
a		array

Examples for this notation are

```
WORD      wFileSize;     // word, i.e. unsigned int
char    * pszCmdLine;    // pointer to a zero terminated string
```

Additionally, constants are specified by capital letters, perhaps separated by underscores, e.g.

```
#define   HKEY_CURRENT_USER    0x80000001
```

Standards for C++ are not yet common. However, one can extend the Hungarian Notation to include classes and members.

Classnames should start with a capital letter, prefixed by 'C' (Microsoft standard), e.g.

```
class   CElementOperationList;
```

Instances of classes, i.e. **objects**, should give a hint to the name of the class. This may be achieved in either of two ways:

- with prefixes, e.g.

  ```
  CElementOperationList   eolTriangles;
  ```

  It may be mentioned that these prefixes cannot be unique, because they should be as short (about 3 characters) but also as informative as possible. Non-uniqueness does not matter because of the usually very limited scope of objects. They may be distinguished from prefixes of standard C-types by their length, and from member functions by not being verbs.
- with meaningful object names, prepended by an "a", e.g.

  ```
  CElementOperationList   aTriangleList;
  ```

Member functions should use verb/(attribute/)object notation, e.g.

```
CEllipse   createEllipticRegion();
```

where the verb is spelled in small letters. (Sometimes in C++ object/verb notation is used: e.g. WindowDestroy, however despite its more object-oriented approach its not widely used, perhaps because of its difficult readability.)

It may be observed that with this definition, member functions give no indication of their return type. The only exception is when the member function returns a reference to an object. If the object was created with new inside the member function, this is perfectly legal, but the caller must be informed that he is responsible for deleting the object. As a hint an "**R**" in front of the object is used:

```
CEllipse&  createREllipticRegion();
```

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