EFFECT OF CONFINEMENT ON FLEXURE BEHAVIOR OF REINFORCED CONCRETE BEAMS USING CONVENTIONAL STEEL STIRRUPS

By

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(2011-NUST-MS Ph.D-Str-16)

This thesis is submitted in partial fulfilment of
the requirements for the award of degree of

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in

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National Institute of Civil Engineering (NICE)
School of Civil & Environmental Engineering (SCEE)
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DEDICATED

TO

MY PARENTS, TEACHERS

AND

WELL WISHERS

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ABSTRACT

Failure of reinforced concrete beams is either governed by reinforcing steel or compression concrete depending on relative resistance provided by these two materials to the applied bending moments. Failure initiated by compression concrete is brittle in nature and is not allowed by codes of practice. It is, however, recognized from applications to columns that confinement of concrete improves both ductility and strength of concrete members. Applicability of this concept of confinement to the reinforced concrete beams has been studied in this research program. Eight reinforced concrete beams were tested in this study. The specimens included four under reinforced and four over reinforced beams. In both types of beams, the stirrup spacing was less than required by normal shear design. The spacing was reduced in flexural span only. Two of the under reinforced beams and two of the over reinforced beams had stirrup spacing equal to 2.5 in and remaining four beams, two under reinforced and two over reinforced, had stirrup spacing of 3.5 in. It was concluded from experimental testing that beams with less stirrup spacing had better ductility, especially in case of over reinforced beams. However, effect on strength is negligible.

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1 INTRODUCTION

1.1 GENERAL

Engineers have been designing structures for centuries. A good structure should have ductility and be able to give warning signs before failing completely. No or less ductility can lead to disastrous failure of structures which can lead to loss of human lives. It is very well known that concrete is a brittle material and it fails abruptly. Confinement is a measure to ensure a relative ductile behavior of concrete.

Concrete having compressive strengths of more than 60MPa can be produced using available materials and conventional methods of mixing, placing and curing. It is generally accepted that increased ductility and strength is exhibited by confined concrete, however there is a difference of opinion on the enhancement of ductility and strength. The basic philosophy for the use of confinement is that it is capable of increasing the capacity of the concrete structures in order to sustain large deformations in the post elastic range without a substantial strength loss [1].

The one obstacle which limits the use of concrete widely is its brittle nature. It is a known fact that ductility ensures large deformations to take place under overload conditions. Large deflections are a good warning sign in the form of tensile cracks that appear before a beam or any other part of the structure fails completely.

1.2 FLEXURE THEORY FOR BEAMS

When a load is applied on a reinforced concrete beam, the bending moment produced in it is resisted by the flexural stresses developed within the member. These stresses are tensile in nature in the region below the neutral axis and compressive in nature above the neutral axis of the beam. The compressive stresses above the neutral axis are resisted by the concrete while the tensile stresses are resisted by the longitudinal reinforcement. These forces then together produce a couple which, as a result, resists the applied load on the beam.

Beams failure in flexure occurs either due to compression concrete or due to the tensile reinforcement depending upon relative resistance provided by these materials. Failure caused by concrete is brittle in nature and may lead to a disastrous aftermath. Failure by the yielding of steel is ductile in nature and is exhibited by large deformations and cracking while providing sufficient time for preventive measures. Therefore, codes of practice restrict the amount of tensile reinforcement such that the failure should be initiated by yielding of longitudinal steel. Such beams are known as under-reinforced beams and those in which the failure is governed by the crushing of concrete are known as over-reinforced beams.

1.3 CONFINEMENT

The codes of practice do not allow the use of over-reinforced beams in reinforced concrete structures because of their brittle nature of failure at ultimate conditions. Lateral stresses are developed when compressive loads are applied and cause splitting of concrete by inducing internal tensile stresses. Confinement stirrups come into action and apply passive confining pressure and restrain the lateral expansion of concrete due to the applied compressive loads. Provision of confining steel stirrups in columns as allowed by the codes of practice show that concrete compression regions are required to be confined for improved behavior. In the case of beams the codes of practice do not allow the proposition of provisions of these confining stirrups for confining purposes but for the sole requirements of shear forces only.

It has been recognized that the strength as well as deformability of concrete substantially increases wherever the amount of confinement in the form of ties or hoops is increased [2]. Enhancing the properties of concrete compression regions can result in improving the flexural behavior of reinforced concrete beams. This can be achieved by restraining the tensile stresses developed in these regions and utilizing the enhanced ductility and strength through the use of transverse reinforcement.

1.4 SCOPE

The scope of this research is to study the effect of confinement on the flexure behavior of reinforced concrete beams of two types: under-reinforced and over-reinforced concrete beams. Generally, at the end, it is a research to study the effects of confinement on the flexure behavior, i.e. ductility and strength, of reinforced concrete beams. Over-reinforced concrete beams can be designed for increased loading capacity and reduced sections, which is not permitted in prevalent codes of practice. With this study, a rationale could be developed for design of such beams with confinement stirrups for increased ductility. In this research, additional experimental evidence will be provided for achievement of additional strength and ductility due to confinement stirrups in the over-reinforced concrete beams. The amount of confinement reinforcement in relation to strength and ductility will also be investigated.

1.5 OBJECTIVES

The objectives of the research are to investigate the possibility and achieving of confinement of compression concrete in under-reinforced and over-reinforced concrete beams with the provision of lateral stirrups. The required data from the experiments will be obtained to find a rationale for existence and quantification of ductility and strength due to confinement through lateral reinforcements in beams.

1.6 METHODOLOGY

Literature review regarding the studies and research on the flexural behavior of confined reinforced concrete beams has been carried out. The experimental study devised is based on the review. Eight full scale beams having moderate longitudinal reinforcement and common stirrups at the perimeter of the entire cross-section were cast and tested. These samples are described as under:

- Under reinforced concrete beams with confinement stirrups in the central region having spacing of 2.5 inches (2 nos.).

- Under reinforced concrete beams with confinement stirrups in the central region having spacing of 3.5 inches (2 nos.).

- Over reinforced concrete beams with confinement stirrups in the central region having spacing of 2.5 inches (2 nos.).

- Over reinforced concrete beams with confinement stirrups in the central region having spacing of 3.5 inches (2 nos.).

2 LITERATURE REVIEW

2.1 GENERAL

Concrete confined by stirrups in the axial compression zone has greater ultimate strength and ductility than the concrete with free lateral strain. Stirrups tend to decrease the lateral strain of the concrete element subjected to axial compression load causing lateral compression in it. It leads to greater ultimate capacity and ductility of the concrete element. That effect is particularly expressed at columns subjected to axially compression load where an increase in the lateral reinforcement can significantly increase the ultimate compressive strength of the concrete and ultimate carrying capacity of the confined column. By an increase in the eccentricity of axial longitudinal compression load the effect of stirrups on uniaxial ultimate compressive strength of concrete element is reduced (Liu *et al.* 2000). The smallest effect takes place in the case of bending of a concrete element [3].

Recently the beneficial effects of confinement have also been utilized for improvement of structural behavior of reinforced concrete beams. The provision of confinement increases the flexural ductility of a beam section in two ways. First it increases the strength of the concrete, resulting in a higher balanced steel proportion (p_{max}). Second it increases the flexural ductility of the beam due to the increased ductility of the triaxially stressed concrete. Mansur et al. found that a volume of fraction of ties in excess of 2.6% provides a negligible gain in ductility when ties are used for confinement. They found that after the spalling of the concrete cover the residual capacity of the beam is governed by the volume fraction of confining ties rather than the strength of the concrete. Adding confinement to an over-reinforced section has no effect on the flexural stiffness but there is a slight increase in the flexural strength of the reinforced beam before the peak resisting moment. At the post-peak stage the confining stresses increase the residual moment resisting capacities of the beam, increasing the flexural ductility. In an over-reinforced section the depth of the neutral axis at first remains at a constant value when both the concrete and the steel reinforcement are elastic. Afterwards it starts to increase when the materials become inelastic. After entering into the post-peak stage the depth of the neutral axis continues to increase until it reaches a certain maximum value.

Adding confinement to an under-reinforced section of a concrete beam has no effect on the moment-curvature relationship before the peak resisting moment. However the ductility improves in the post-peak region. In an under-reinforced section the depth of the neutral axis at first remains at a constant value when both the concrete and the steel reinforcement are still elastic and then decreases to a minimum value when the materials become inelastic. However after entering into the post-peak stage the depth of the neutral axis starts to increase. This happens in both the unconfined and confined concrete beam sections. The provision of confinement in an under-reinforced section has the effect of slowing down the rate of increase of the neutral axis depth at the post-peak stage [4].

Confinement can be in the form of tie stirrups or helix. Helical confinement is more effective than rectangular ties when it comes to increasing the strength and ductility of confined concrete. The reason behind this is that a helix applies a uniform radial stress along the concrete member, whereas a rectangle tends to confine the concrete at the corners. The effectiveness of the confinement is affected by several variables like the helical pitch, helix yield strength and the helix bar diameter. Stresses in the helices are negligible when a helically confined beam is loaded. As the load increases the stresses within the helix increase and as a result, due to Poisson’s effect, the confining stresses will increase and confinement will commence. Confinement does not increase strength or ductility in the early stages but when the axial stress is about 60% of the maximum cylinder strength then the concrete can be said to be effectively confined [5].

2.2 CONFINEMENT IN RC BEAMS

Experimental studies of effect of provision of stirrups on the ultimate strength capacity of concrete beams subjected to pure bending are still preferred where the failure of the beam takes place in the form of crushing of concrete in the compression zone. Various researchers conducted studies on the effect of confinement on the behavior of beams. An overview of the previous research on beam confinement is provided in succeeding paragraphs:

2.2.1 Base and Read (1965)

Thirteen reinforced beams and three pre-stressed beams having cross-sections of 152 mm x 280 mm and 3000 mm long. There were under-reinforced, over-reinforced and balanced section beams and all were tested using one-point loading mechanism. Some of the beams were confined using steel stirrups only and some with stirrups and helical confinement. Tie spacings were 50 mm and 203 mm; helical pitch was 50 mm and 25 mm and helical reinforcement diameters were 6.35 mm and 4.76 mm. The size of the confined core was 82 mm.

2.2.2 Shah and Rangan (1970)

Twenty-four group of beams were casted to study the effect of confinement. The beams had a cross-section of 50.8 mm x 76.2 mm and the length of 914.4 mm. Each group had two identical beams which were tested under the four-point loading mechanism and these beams contained different amount of steel with different configuration such as steel fibers, longitudinal compression steel and tie stirrups.

The beams confined with tie stirrups showed more ductility than the other beams confined with other forms of steel.

2.2.3 Ziara et al (1995)

Twelve reinforced concrete beams were casted by Ziara et al in order to investigate the influence of confinement on the behavior of beams. Four beams had no confinement and the rest of the eight beams had their compression regions confined with tie stirrups.

As a result the confinement did not significantly increase the flexural capacity of the beams but it did, somehow, improve the ductility of the beams due to the confinement of the compression region at mid-span.

2.2.4 MNS Hadi et al (2010)

Five beams were designed, constructed and tested according to AS3600 in order to examine the effect of different types of confinement at the compression zone of each beam. Out of the five beams the first beam was the reference beam while the other four were designed with different arrangements of confining reinforcement promoting ductile failure to determine the effectiveness of the confining reinforcement in the compressive region of the beams. All five beams were over-reinforced for brittle failure in accordance with AS 3600. All beams had the same dimensions: length 4000 mm, height 300 mm and width 200 mm. Concrete used for the beams had the compressive strength of 85 MPa. Out of the five beams, there was a) one reference beam, b) one beam with horizontal ties with stirrups along the beam with 50 mm spacing, c) one beam with vertical ties and stirrups along the beam at 50 mm spacing, d) one beam with double helix with stirrups at mid-span at 100 mm spacing and e) one beam with single helix with stirrups along the beam at 100 mm spacing at mid-span. All these beams had different forms of reinforcing confinement in their compression zones. Four-point loading was used to test the beams.

The aim of this research program was to improve the ductility of high strength concrete beams using helices in the compression area of the beam. As a conclusion the results were encouraging and showed that the strength and ductility of an over-reinforced beam can be increased by using helical reinforcement. The reduced ductility, due to the increase in tensile steel and the use of high strength concrete was overcome through the use of helical reinforcement in the compression region of the beam.

Similar research work has been carried out by Hadi and Elbasha (2007), Hadi and Schmidt (2002) and Jeffry and Hadi (2008) having tested the effect of different confinement shapes on the behavior of reinforced concrete beams. Results of testing proved that placing helixes with different diameters as a variable parameter in the compression zone of reinforced concrete beams improve their strength and ductility.

2.2.5 Jure Radnić et al (2013)

The experimental testing of concrete beams subjected to pure bending were done in which the failure occurs by concrete crushing in the compression zone. Effects of stirrups form and spacing and concrete strength on the ultimate strength capacity and ductility of the analyzed beams was researched. Three identical beam samples were made and tested for each case.

Length of the beam was 2.2 m by span of 2.0 m with a rectangular cross-section. Width of the beam was 60 mm with a variable height: 150 mm at the mid-span and 500 mm at the supports. The beam height by the supports being greater than at the mid-span and with strong vertical and horizontal reinforcement at that length was adopted in order to avoid shear failure of the beam by the supports and to achieve its failure at the mid-span due to pure bending. The beam was loaded so that there were no shear forces at its middle length. The bottom zone of the beam was reinforced by strong longitudinal tensile reinforcement; thus, the beams failure was always occurred by concrete crushing in the upper compression zone at the length of beam height of 150 mm.

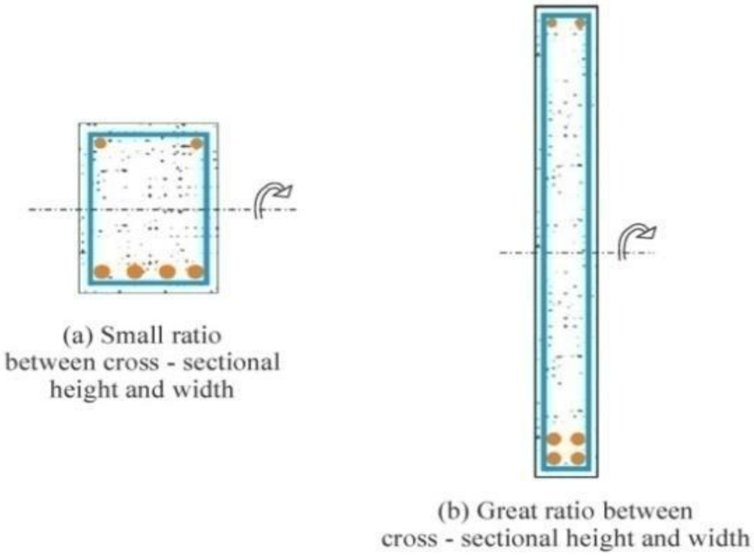
The aim of this research was to confirm the existing knowledge and to obtain new ones on stirrups effect on strength capacity and ductility of concrete beams with compression failure of concrete.

The conclusion of the research work was that the ultimate strength capacity and ductility of the tested concrete beams increased with the decrease in stirrups spacing. It was found out that the stirrups that enclose concrete in the compression zone are more efficient than the common stirrups at the perimeter of the entire beam cross-section.

Stirrups form has a great effect on the ultimate carrying capacity and ductility of the beams.

2.3 EFFECT OF BEAM CROSS-SECTION ON BEAM STRENGTH

The size or the form of a beam cross-section also affects the concrete ultimate compressive strength (see Fig. 1). Since stirrups induce lateral pressure on concrete and spatial stress state in the concrete element, different ultimate strength capacity and ductility shall be expected for beams with different height and width ratio of the beam cross-section. For a smaller height and width ratio of a beam cross-section, greater the effect of stirrups is expected.



(a) Small ratio between cross - sectional height and width

(b) Great ratio between cross - sectional height and width

Fig. 1: Some forms of beam cross-section

2.4 EFFECT OF FORM OF STIRRUP ON COMPRESSIVE STRENGTH

Concrete ultimate compressive strength is also affected by the form of the stirrups (see Fig. 2). Common stirrups at the perimeter of the entire cross-section, as shown in Fig. 2(a), will provide a relatively small increase in ultimate compressive strength of concrete. Stirrups shown in Fig. 2(b) will provide greater lateral pressure on the compressive zone of concrete followed by greater ultimate compressive strength and ductility of the concrete. Number, spacing and diameter of longitudinal compression steel bars as well as maximum aggregate grain and other parameters will also affect on the ultimate strength capacity and ductility of a concrete beam [6].

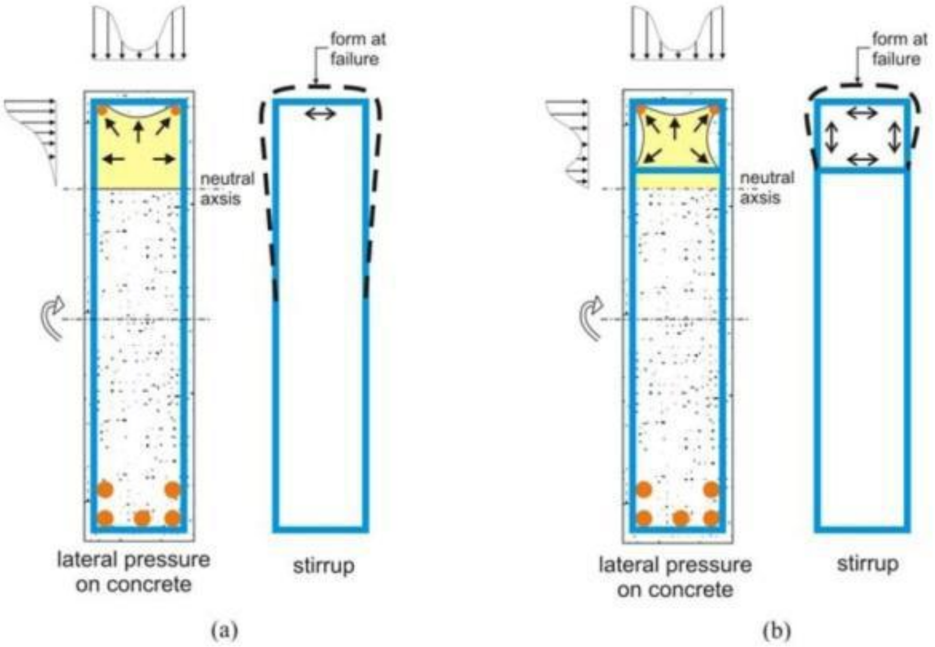


Fig. 2: Effects of stirrup form on lateral pressure of concrete and stirrup deformation at compression concrete failure of beam

3 EXPERIMENTAL PROGRAM

3.1 GENERAL

In this chapter the results of an experimental research program on ordinary strength reinforced concrete beams are presented. Eight confined full scale beams, four of them under-reinforced and four over reinforced, were cast and tested primarily to study the effect of confinement on the flexural strength of the beams.

3.2 DETAILS OF BEAMS

All the eight beams were casted in one batch of concrete. The cross sections of the beams were 200 mm x 300 mm. The length of the beams was 3350 mm (11 feet). The details of the beams are shown in Fig 3.1. The beams constructed were of two types:

i) Under reinforced beams.
ii) Over reinforced beams.

There were two under-reinforced beams with the spacing of stirrups was 63.5 mm (2.5 in.) c/c and two under-reinforced beams with the spacing of 88.9 mm (3.5 in.) in the flexural span. Similar case was with the four over-reinforced beams.

The alphanumeric i.e. **UR-1** is used to represent the name of the beam which UR stands for Under-Reinforced beam and 1 is the number of the beam. Similarly the alphanumeric **OR-1** is used, with OR standing for Over-Reinforced. The details and section are given in Fig 3.11-3.14 in Appendix I.

3.3 MIX DESIGN

In the study $f''c$ was selected as 28MPa (4000psi) but the observed strength was 30MPa (4400 psi). The mix design as given in Table 3.1 – Appendix I was used.

3.4 MATERIALS

3.4.1 Cement

The Type I cement conforming to ASTM C 150 – 04 was used. Results of the tests carried out to ascertain the properties of cement are presented in Table 3.2 – Appendix I.

3.4.2 Fine Aggregates

Locally available sand (Lawrencepur Sand) was used. Results of the tests conducted for verification of properties of sand are tabulated in Table 3.3 – Appendix I. The gradation of the fine aggregate is tabulated in Table 3.4 - Appendix I. Fineness modulus of sand was calculated as 2.66. Particle size distribution graph for the fine aggregates in shown in Fig. 3.9-Appendix I.

3.4.3 Coarse Aggregates

Aggregate from Margalla crush site was used in this research. Maximum size for the aggregate was kept as 19 mm (0.75 in.). The laboratory test results are tabulated in Table 3.5 - Appendix I. The gradation and sieve analysis was determined in accordance with ASTM C 136 – 01 and tabulated in Table 3.6 - Appendix I. Particle size distribution graph for the coarse aggregates in shown in Fig. 3.10-Appendix I.

3.4.4 Reinforcing Steel

Reinforcement bars of #8 and #9 sizes were used as longitudinal tensile reinforcement. #3 bars were used as transverse reinforcement. The grade 60 steel was used for longitudinal and transverse reinforcement but the observed yield strength of all the steel rebars was more than 70ksi. Specification of specimens and material properties of the reinforcement bars are shown in Table 3.7-Appendix I.

3.4.5 Admixture

Plastiment P-200 (product of Ultra Chemical Company) is an admixture which was used in the research. The dosage was maintained throughout the research work in between 0.5 %-1.5 % by weight of cement.

3.4.6 Water

For mixing and curing of the concrete potable water was used.

3.4.7 Strain Gauges

Three electrical strain gauges were installed on each beam in the central flexure portion. The length of each strain gauge was 6 mm and the width 3 mm. The strain gauges were from Vishay Micro Measurements (origin of USA). The specification of foil strain gauges type was EA-06-240LZ-120/E. These gauges had 120.0+ 0.3 % grid resistance in ohms with gauge factor of 2.080 ± 0.5 at 24 °C and are manufactured with self-temperature compensation characteristics to minimize the thermal output. The EA series gauges are a general purpose family of constant alloy strain gauges widely used in experimental stress analysis. They are constructed with a 0.03-mm tough flexible polyamide film backing. Strain gauges were soldered and checked for continuity with the help of digital multi-meter. One gauge was pasted on the longitudinal reinforcement bar to monitor the elongation of steel in the tension region, second gage was pasted on the hanger bar of beam to monitor the compressive strain at mid-section of the beam and the last gauge was pasted on the confinement stirrup to check the effect of lateral strain on the beam during bending.

3.5 Casting of Specimens

Specimens were cast as per ASTM C 31 and 31M. Eight beams were prepared with single batch of concrete procured from a batching plant. For determination of the compressive strength of concrete 12 cylinders of size 150 mm x 300 mm (6”x12”) were also prepared. 2 cylinders were tested after 7 days, 2 cylinders after 14 days and the remaining 8 cylinders were tested after 28 days of casting. Slump of the concrete at the time of pouring was 62 mm which falls in between the design slump range of 25-75 mm.

3.6 Description of Specimens

Eight reinforced concrete beams were cast to investigate the effect of confinement on the flexure behavior. These beams having longitudinal tensile steel reinforcement ratio of 1.70 % for under-reinforced and 3.20 % for over-reinforced beams were divided into two series depending upon whether they were simply under-reinforced or over-reinforced. The cross-sectional dimensions of all the eight beams were 200mm x 300 mm (8” x 12”). The specification of specimens and material properties are shown in Table 3.7 - Appendix I. Test results of concrete cylinder strength are shown in Table 3.8 - Appendix I.

3.7 Fabrication of Specimens

Casting of specimens was done as per ASTM C 31/31M. The specimens were cast in 25 mm (1 in.) thick plywood shuttering. Shuttering was prepared in such a manner that it could be dismantled easily. The steel reinforcement cages with installed strain gauges were placed in the formwork over the 25 mm (1 in.) spacers and tied up with the bars. The concrete for the beams was mixed in a batching plant set up near SUPARCO office, Islamabad. The concrete was poured manually in the specimens by the use of wheel-barrows as the batching plant was very near to the site where casting of the specimens took place. The formwork was removed from the beams after 48 hours. Hessian cloth was placed on the beams and cured in open whereas test cylinders were cured in water. After 28 days the specimens were transported from the site to NUST.

3.8 TESTING OF SPECIMENS

3.8.1 Test Setup

The testing facility established at SCEE, NUST was used for this experimental program. The load was applied through a hydraulic jack and pump having 120 tons capacity. The beams were placed on the supports with the help of a gantry crane. The supports comprised of 100 mm (4 in.) dia. solid steel bars, making the beam simply supported at both ends. The load was applied using remote control in increments of 1.5 tons which was displayed at the display panel. A steel girder was used to apply two-point loading at shear span of 1000 mm from both sides. Three LVDTs were placed under the beam at mid span and at quarter points to measure the deflections at these points. Deflections were measured and recorded through the structural load analysis and data logging system.

3.8.2 Testing Procedure

The beams were planned to be tested under two point loading. The load was applied after centering and aligning the specimens on the test setup and making all necessary arrangements for recording the load and deflection. The load was applied in increments of 1.5 tons and deflections recorded at each load increment. During the application of load, the cracks were observed and marked on the beams.

4 EXPERIMENTAL RESULTS

4.1 CONCRETE STRENGTH

Twelve cylinders were cast in total at the time of pouring of concrete in specimens. Two cylinders were tested after 7 days, two were tested after 14 days and eight cylinders were tested after 28 days. The average compressive strength obtained was 4400 psi for eight cylinders tested after 28 days.

4.2 RECORDING MEASUREMENTS

4.2.1 Deflections

Dual mechanism for recording of deflections was adopted. Electronic LVDTs were installed for each specimen. Measurements from electronic LVDTs were recorded through the computer.

4.3 TESTING BEHAVIOR OF SPECIMENS

Testing of all eight specimens was carried out at NUST Laboratory. The samples were loaded at two points. Load was applied in increments of 1.5 tons. After each increment of load, cracks in the beams were observed and marked. Deflections were also noted after each increment of load. Detailed behavior of each specimen is as under:-

4.3.1 Specimen UR-1

This was an under-reinforced beam with the stirrup spacing of 63.5 mm (2.5 in.) c/c in the flexural span. Initial flexural cracks appeared at a load of 12 tons. These cracks increased in length at the load of 26 tons. Some cracks in the center flexure region appeared at the loads of 15 tons and 18 tons.

Inclined shear cracks near the supports appeared at the load of 12 tons which started to grow towards the load points. Some of these cracks did not propagate while some of them increased in length up to the load of 25 tons. The beam failed at the load of 27 tons. The failure was due to the crushing of the compression concrete.

Load deflection plot is given in Figure 4.1-Appendix II. Deflected shape of the beam at various stages of loading is displayed in Figure 4.5-Appendix II. Moment-curvature plot is given in Figure 4.17-Appendix II.

4.3.2 Specimen UR-2

This was an under-reinforced beam with the stirrup spacing of 63.5 mm (2.5 in.) c/c in the flexural span. Flexural cracks of small length started to appear in the beam at the load of 8 tons. These flexure cracks further propagated up to 16 tons, some eventually stopping at 20 tons.

Inclined cracks near the supports started to appear at the load of 16 tons. Some inclined cracks appeared at 20 tons and increased in length up to the loading of 25 tons. At 25 tons the concrete on the right support started to disintegrate. The beam failed at 28 tons due to the crushing of the compression concrete.

Load deflection plot is given in Figure 4.3-Appendix II. Deflected shape of the beam at various stages of loading is displayed in Figure 4.4-Appendix II. Moment-curvature plot is given in Figure 4.18-Appendix II.

4.3.3 Specimen UR-3

This was an under-reinforced beam with the stirrup spacing of 88.9 mm (3.5 in.) c/c in the flexural span. Small flexural cracks close to mid span started appearing at 8 tons and increased in length up to 17 tons. Some cracks appeared directly at the loads of 17 tons and 21 tons.

Inclined cracks near both the supports emerged at the load of 17 tons and increased in size and length. Some inclined cracks propagated in length at the load of 24 tons and some cracks which started at 24 tons joined with the crack lines of 17 tons load near the supports. The beam failed at 25 tons due to the inclined cracks.

Load deflection plot is given in Figure 4.5-Appendix II. Deflected shape of the beam at various stages of loading is displayed in Figure 4.6-Appendix II. Moment-curvature plot is given in Figure 4.19-Appendix II.

4.3.4 Specimen UR-4

This was an under-reinforced beam with the stirrup spacing of 88.9 mm (3.5 in.) c/c in the flexural span. Flexural cracks started to appear in the middle region of beam at 7 tons. These cracks started to get slightly inclined at 10 tons near the point loadings. Growth of flexural cracks continued up to 15 tons.

Inclined cracks near the supports appeared at 12 tons near the supports and continued to grow towards the point loads. These cracks propagated up to the load of 18 tons. The beam failed at the load of 25 tons and concrete spalled off in the shear span between the support and the point load on one side of the beam.

Load deflection plot is given in Figure 4.7-Appendix II. Deflected shape of the beam at various stages of loading is displayed in Figure 4.8-Appendix II. Moment-curvature plot is given in Figure 4.20-Appendix II.

4.3.5 Specimen OR-1

This was an over-reinforced beam with the stirrup spacing of 63.5 mm (2.5 in.) c/c in the flexural span. Cracks first started to appear at the load of 13 tons in the center portion, i.e. the flexure portion of the beam. More cracks then appeared in the flexure portion at the load of 25 tons which did not propagate further.

Inclined shear cracks near the supports began appearing at the load of 21 tons and started to grow towards the load points. These cracks then increased in length up to the load of 25 tons. Some cracks started at 25 tons and later on joined together to form a single crack which then propagated up to the load of 33 tons. The beam failed at the load of 42 tons.

Load deflection plot is given in Figure 4.9-Appendix II. Deflected shape of the beam at various stages of loading is displayed in Figure 4.10-Appendix II. Moment-curvature plot is given in Figure 4.21-Appendix II.

4.3.6 Specimen OR-2

This was an over-reinforced beam with the stirrup spacing of 63.5 mm (2.5 in.) c/c in the flexural span. Flexural cracks started appearing at 12 tons. These cracks then propagated in length up to the load of 20 tons.

At 24 tons inclined cracks long in length appeared and started to grow towards the load point. The beam failed at the load of 25 tons due to the failure of the compression concrete.

Load deflection plot is given in Figure 4.11-Appendix II. Deflected shape of the beam at various stages of loading is displayed in Figure 4.12-Appendix II. Moment-curvature plot is given in Figure 4.22-Appendix II.

4.3.7 Specimen OR-3

This was an over-reinforced beam with the stirrup spacing of 88.9 mm (3.5 in.) c/c in the flexural span. Flexural cracks started to appear in the middle region of beam at 10 tons. These cracks started to get slightly inclined at 23 tons. Growth of flexure cracks continued up to 28 tons. There was one single crack with the highest load in the flexure region at 33 tons.

Inclined cracks appeared at 23 tons near the supports and continued to grow towards the points of loading. The cracks increased in length up to the load of 28 tons and widened at the load of 38 tons. A few small cracks appeared near the supports at the loads of 33 tons and 38 tons. The beam failed both by crushing of concrete and widening of inclined cracks at 40 tons.

Load deflection plot is given in Figure 4.13-Appendix II. Deflected shape of the beam at various stages of loading is displayed in Figure 4.14-Appendix II. Moment-curvature plot is given in Figure 4.23-Appendix II.

4.3.8 Specimen OR-4

This was an over-reinforced beam with the stirrup spacing of 88.9 mm (3.5 in.) c/c in the flexural span. Flexural cracks appeared at 13 tons and increased in length up to 18 tons. One flexure crack appeared at 20 tons and propagated in length up to the load of 30 tons. Two small cracks appeared at the load of 18 tons and 33 tons and did not increase in length.

At 20 tons inclined cracks appeared near the supports and started to grow towards the loading points. These cracks then increased in length up to the load of 33 tons. Some inclined cracks appeared at 15 tons and went in length up to the load of 20 tons and further increased up to the load of 33 tons. A few cracks appeared at the load of 28 tons and remained small in length. The beam failed at the load of 34 tons due to the crushing of the compression concrete.

Load deflection plot is given in Figure 4.15-Appendix II. Deflected shape of the beam at various stages of loading is displayed in Figure 4.16-Appendix II. Moment-curvature plot is given in Figure 4.24-Appendix II.

4.4 SUMMARY OF BEHAVIOR

Summary of the behavior of the beams is summarized below:

- Initial cracking load range for the **UR** series (under-reinforced) is from 7-12 tons and for the **OR** series (over-reinforced) is 10-13 tons.

- Failure of the **UR** series took place in the range of 25-28 tons and for the **OR** series the range was 34-42 tons.

- Existing flexural cracks extended and new flexural cracks appeared in the beam by the increase in load. The flexural cracks in the shear spans started to incline at loads of 12 tons for the **UR** series, whereas for the **OR** series the load was 20 tons.

- The angle of the inclined cracks was observed to be around 45 degrees.

5 RESULTS & DISCUSSION

The aim of this experimental program was to investigate the possibilities and achieving of confinement of compression concrete in under and over-reinforced beams. Four beams were under-reinforced and the remaining four were over-reinforced. Two of the under reinforced beams had stirrups c/c at 63.5 mm (2.5 in.) and the remaining two beams 89 mm c/c (3.5 in.). Over-reinforced beams also had similar arrangement of stirrups. Load deflection response, moment–curvature relationship and ductility indices were analyzed and compared in order to evaluate the difference in behavior of the two types of beams.

For the purpose of discussion in this chapter, under-reinforced beams are represented with “UR” and over-reinforced beams with “OR”. Subscript “2.5” and “3.5” are used to represent center-to-center spacing of the steel stirrups in each case.

5.1 Interpretation of results

5.1.1 Load- Deflection Response

The load-deflection response for the $UR_{2.5}$ beams was different from that of $UR_{3.5}$ beams. The peak loads remained almost the same while maximum deflections are higher in the case of $UR_{2.5}$ beams. The average peak load carried by $UR_{2.5}$ beams is 26.7 tons as compared to the peak load of 25.1 tons for the $UR_{3.5}$ beams. Average maximum deflection values are 33.87 mm and 25.73 mm for $UR_{2.5}$ beams and $UR_{3.5}$ beams respectively. The results of the load-deflection data reveal that $UR_{2.5}$ beams provided better deflection response as compared to $UR_{3.5}$ beams.

Similarly the load-deflection response for the $OR_{2.5}$ beams was different from the $OR_{3.5}$ beams. Peak loads and maximum deflections are higher for the $OR_{2.5}$ beams but the increase in loads is not significant. The average peak load for the $OR_{2.5}$ beams is

38.71 tons as compared to 34.27 tons in $OR_{3.5}$ beams. Average maximum deflection values for the $OR_{2.5}$ beams are 40.88 mm and 28.91 mm for the $OR_{3.5}$ beams.

The load-deflection graph for the $UR_{2.5}$ and $UR_{3.5}$ and that of $OR_{2.5}$ and $OR_{3.5}$ are given in Fig. 5.1 and 5.2-Appendix III.

5.1.2 Moment-Curvature Response

Moment-curvature response for the $UR_{2.5}$ beams was different from the response of the $UR_{3.5}$ beams. Peak moments and maximum curvatures for the $UR_{2.5}$ beams were higher than for the $UR_{3.5}$ beams. The average peak moment and maximum curvature for the $UR_{2.5}$ beams was 135.92 kNm and $37.88x10^6$ rad/mm and for the $UR_{3.5}$ beams was 124.84 kNm and $27.29x10^6$ rad/mm. The results clearly indicate that the $UR_{2.5}$ beams show a more ductile behavior and moment carrying capacity than their counterpart.

Moment –curvature relationship of over reinforced beams indicate that $OR_{2.5}$ beams had improved ductility as compared with $OR_{3.5}$ beams. For $OR_{2.5}$ beams, average peak moment value is 187.3 kNm and average maximum curvature is $29.97x10^6$ rad/mm. These values for $OR_{3.5}$ beams are 172.9 kNm and $20.39x10^6$ rad/mm. The comparison of moment and curvature results shows that $OR_{2.5}$ beams, like their under-reinforced counterparts, have significant improvement in ductility but load-carrying capacity remains almost the same. The average moment-curvature graphs for the $UR_{2.5}$ and $UR_{3.5}$ and that of $OR_{2.5}$ and $OR_{3.5}$ are given in Fig. 5.4 and 5.6-Appendix III.

5.1.3 Ductility Index

Values of ductility index also show that $UR_{2.5}$ and $OR_{2.5}$ beams were more ductile as compared to $UR_{3.5}$ and $OR_{3.5}$ beams. The average values of ductility index for $UR_{2.5}$ beams and $UR_{3.5}$ beams are 3.17 and 3.06. These values for $OR_{2.5}$ and $OR_{3.5}$ are 2.77 and 2.60 respectively. The average ductility index bar charts for the $UR_{2.5}$ and $UR_{3.5}$ and that of $OR_{2.5}$ and $OR_{3.5}$ are given in Fig. 5.7 and 5.8-Appendix III.

5.1.4 Cracking Pattern and Failure Mode

Both vertical and diagonal cracks were critical in case of under-reinforced beams. Final failure of these beams, generally, occurred due to crushing of compression concrete in the flexural span. Intensity of diagonal cracks was more in the case of over-reinforced beams. Failure of these beams was caused by either crushing of compression concrete or due to widening of flexural shear cracks.

5.2 Discussion of Results

The load-deflection response, moment-curvature relationship and values of ductility indices show that the behavior of beams with 6.5 mm (2.5 in.) stirrup spacing was different from the beams with 89 mm (3.5 in.) stirrup spacing. Ductility improved in case of beams with lesser stirrup spacing, as demonstrated by the comparison of respective results.

Curvature of $UR_{2.5}$ beams was 38% more than $UR_{3.5}$ beams and that of $OR_{2.5}$ beams was 47% more than $OR_{3.5}$ beams. Similarly, deflection of $UR_{2.5}$ beams was 31% more than $UR_{3.5}$ beams and that of $OR_{2.5}$ beams was 41% more than $OR_{3.5}$ beams.

5.3 Conclusions

Following conclusions are drawn from this research:

- Ductility of both under-reinforced and over-reinforced concrete beams increase by reducing the spacing of the steel stirrups. The effect is more pronounced in case of over-reinforced beams.

- Load-carrying capacity of both under-reinforced and over-reinforced beams is not significantly affected by the reduction in spacing of steel stirrups.

- Crack penetration rate and cracking pattern was similar for both types of beams, i.e. beams with 63.5 mm (2.5 in.) stirrup spacing and 89 mm (3.5 in.) stirrup spacing.

REFERENCES

1. D Galeota & MM Giammatteo and R Marina, Strength and Ductility of Confined High Strength Concrete, Earthquake Engineering, Tenth World Concference, 1992, Rotterdam. ISBN 9054100605.
2. Ahmad Khaleek, Yadav RK and Chandak Rajeev, Effect of Lateral Confinement on Strength of Concrete, ISCA Journal of Engineering Sciences, Vol. 1(1), 40-44, July (2012).
3. Jure Radnić, Radoslav Markić, Alen Harapin and Domagoj Matešan, Effect of Confined Concrete on Compressive Strength of RC beams, Faculty of Civil Engineering, Architecture and Geodesy, University of Split, 21000 Split, Croatia (Received May 3, 2013, Revised June 15, 2013, Accepted July 29, 2013).
4. MNS Hadi, Flexural Behaviour of High Strength Concrete Beams with Confining Reinforcement, ICCBT2008.
5. MNS Hadi and R Jeffry, Effect of Different Confinement Shapes on the Behavior of Reinforced HSC Beams, Asian Journal of Civil Engineering (Building and Housing) Vol. 11, No. 4 (2010) Pages 451-462.
6. Jure Radnić, Radoslav Markić, Alen Harapin and Domagoj Matešan, Effect of Confined Concrete on Compressive Strength of RC Beams, Faculty of Civil Engineering, Architecture and Geodesy, University of Split, 21000 Split, Croatia (Received May 3, 2013, Revised June 15, 2013, Accepted July 29, 2013).

Appendix I

Description	Details
Cement	410 kg/m^3
Fine Aggregate	584 kg/m^3
Coarse Aggregate	1224 kg/m^3
W/C Ratio	0.43
Mix Ratio	1:1.48:2.96
Admixture	Plastiment P-200, 0.5%-1.5% of weight of cement

Table 3.1 Mix Design

Tests	Test Results	Specifications
Specific Gravity	3.06	ASTM C 188 – 95
Initial Setting Time	150 minutes	ASTM C 191 – 01
Final Setting Time	285 minutes	ASTM C 191 – 01

Table 3.2 Properties of Cement

Tests	Test Results	Specifications
Specific Gravity	2.71	ASTM C 128 – 01
Absorption	0.7%	ASTM C 128 – 01
Fineness Modulus	2.66	ASTM C 33 – 02

Table 3.3 Properties of Fine Aggregates

Sieve No.	Mass Retained (g)	Percent Retained	Cumulative Percent Retained	Percent Passing	
				Actual	ASTM C 33-02
3/8”	0	0	0	100	---
#4	8	1.54	1.54	98.46	95 - 100
#8	42	8.08	9.62	90.38	80 - 100
#16	108	20.77	30.39	69.61	50 - 85
#30	156	30.00	60.39	39.61	25 - 60
#50	136	26.16	86.55	13.45	5 - 30
#100	42	8.08	94.63	5.37	0 - 10
Pan	28	5.39	---	---	---
Total	520	---	---	---	---

Table 3.4 Gradation of Fine Aggregates

Detail of Tests	Test Results
Impact value (percent)	11.4
Crushing value (percent)	21.4
Abrasion value (percent)	15.8
Specific gravity	2.67

Table 3.5 Properties of Coarse Aggregates

Sieve size (mm)	Mass Retained (g)	Percent Retained	Cumulative Percent Retained	Percent Passing	
				Actual	ASTM C 33-02
37.5	0	0	0	100	100
19	72	3.60	3.60	96.40	90-100
9.5	1011	50.55	54.15	45.85	40-70
4.75	898	44.9	99.05	0.95	0-15
Pan	19	0.95	100	0	0-5

Table 3.6 Gradation of Coarse Aggregates

Beams	**f'_c (psi)**	**Longitudinal Tensile Bars**			**Shear Steel Bars**		**a/d**	**d (in)**
		No.	**ρ_l(%)**	**f_{yl} (ksi)**	**No. (Flexure and Shear)**	**f_{yl} (ksi)**		
Under-Reinforced Series								
UR-1	4400	2#8	1.70	74	Flexure: #3 @ 2.5” c/c Shear: #3@5” c/c	72	3.64	7
UR-2	4400	2#8	1.70	74		72	3.64	7
UR-3	4400	2#8	1.70	74	Flexure: #3 @ 3.5” c/c Shear: #3@5” c/c	72	3.64	7
UR-4	4400	2#8	1.70	74		72	3.64	7
Over-Reinforced Series								
OR-1	4400	2#8 1#9	3.20	74	Flexure: #3 @ 2.5” c/c Shear: #3@5” c/c	72	3.64	7
OR-2	4400	2#8 1#9	3.20	74		72	3.64	7
OR-3	4400	2#8 1#9	3.20	74	Flexure: #3 @ 3.5” c/c Shear: #3@5” c/c	72	3.64	7
OR-4	4400	2#8 1#9	3.20	74		72	3.64	7

Table 3.7 Specification of Specimens and Material Properties

Size of Cylinders (in)	Day of Testing	Compressive Strength (psi)
6x12	7	2812
6x12	7	2826
6x12	14	3238
6x12	14	3807
6x12	28	4889
6x12	28	4714
6x12	28	4374
6x12	28	4217
6x12	28	3962
6x12	28	4402
6x12	28	3891
6x12	28	4075

Table 3.8 Compressive Strength of Cylinders

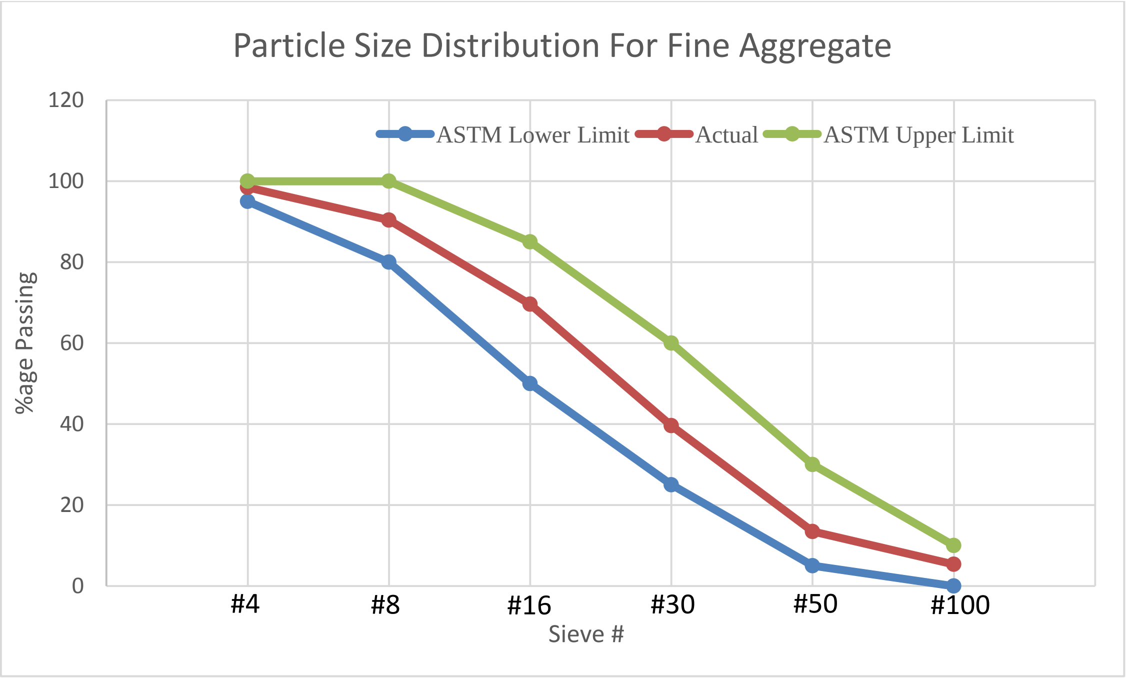


Figure 3.9: Particle Size Distribution of Fine Aggregates

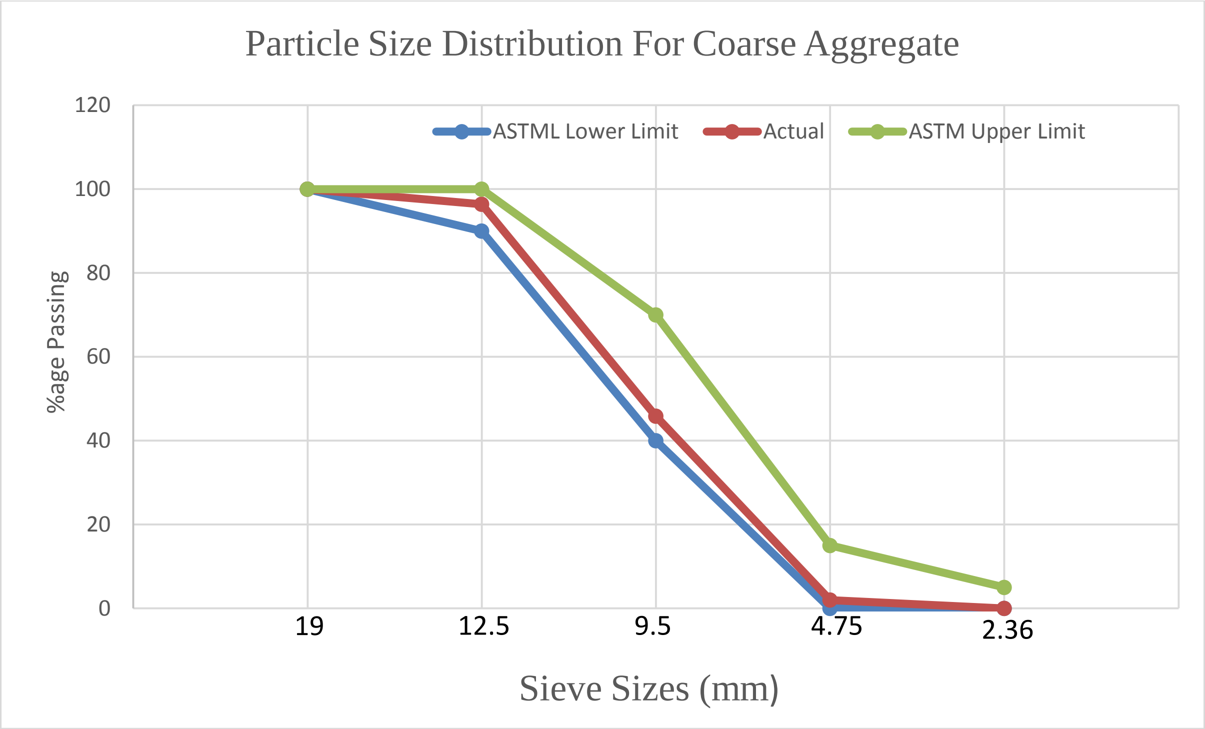


Figure 3.10: Particle Size Distribution of Coarse Aggregates

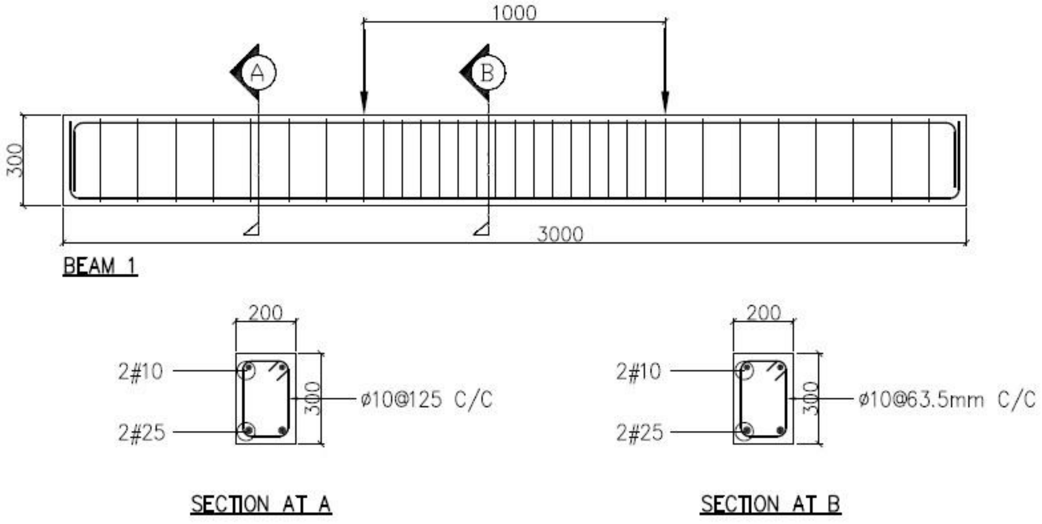


Figure 3.11: Details of Specimen UR-1 and UR-2

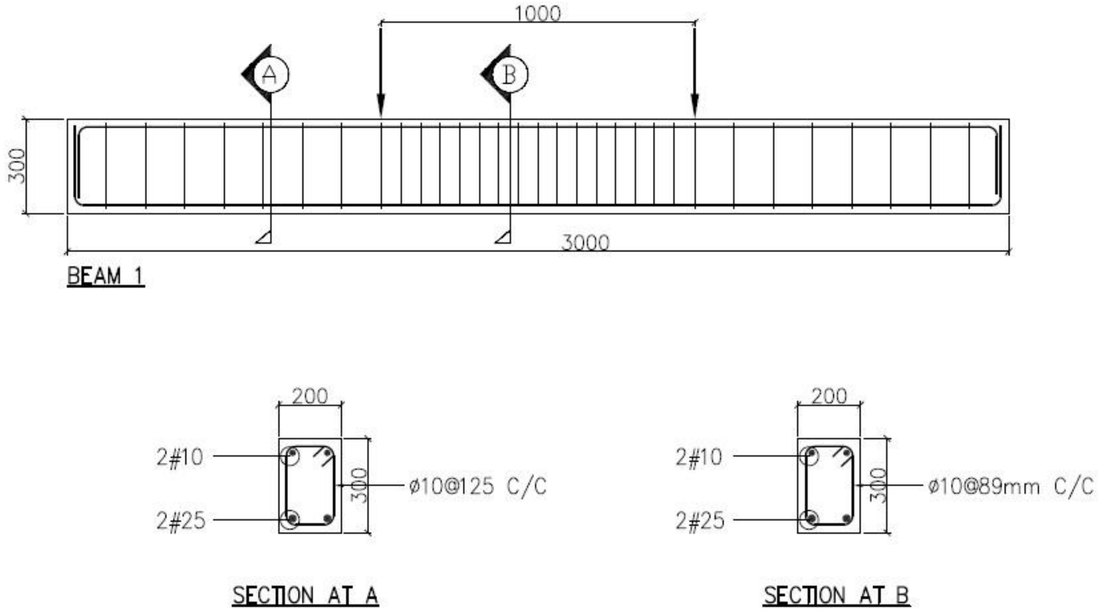


Figure 3.12: Details of Specimen UR-3 and UR-4

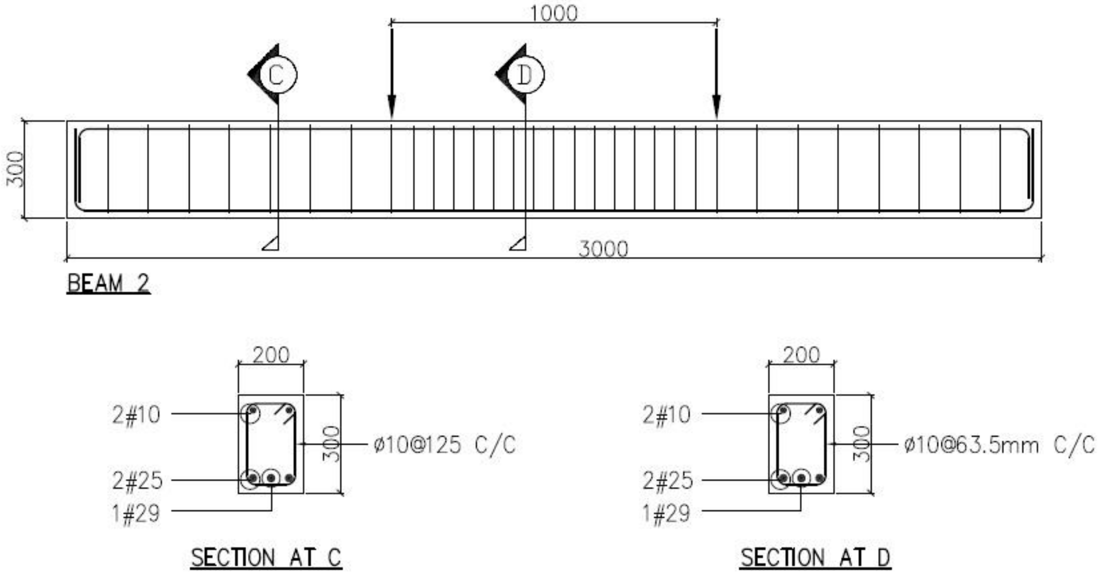


Figure 3.13: Details of Specimen OR-1 and OR-2

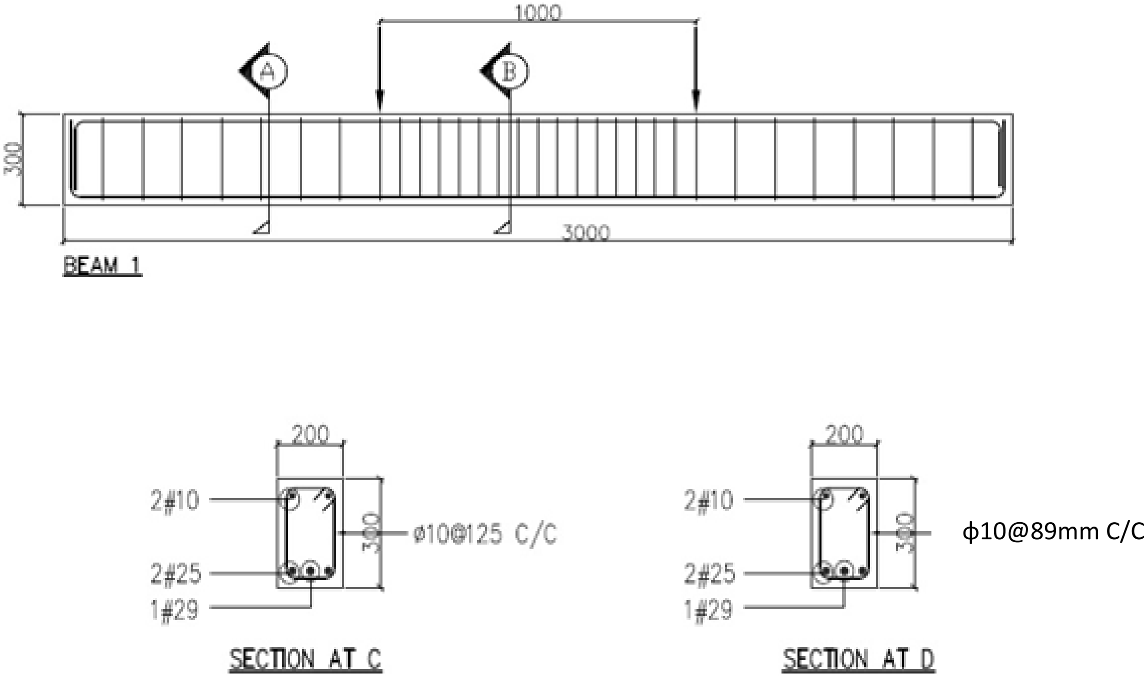


Figure 3.14: Details of Specimen OR-3 and OR-4

APPENDIX II

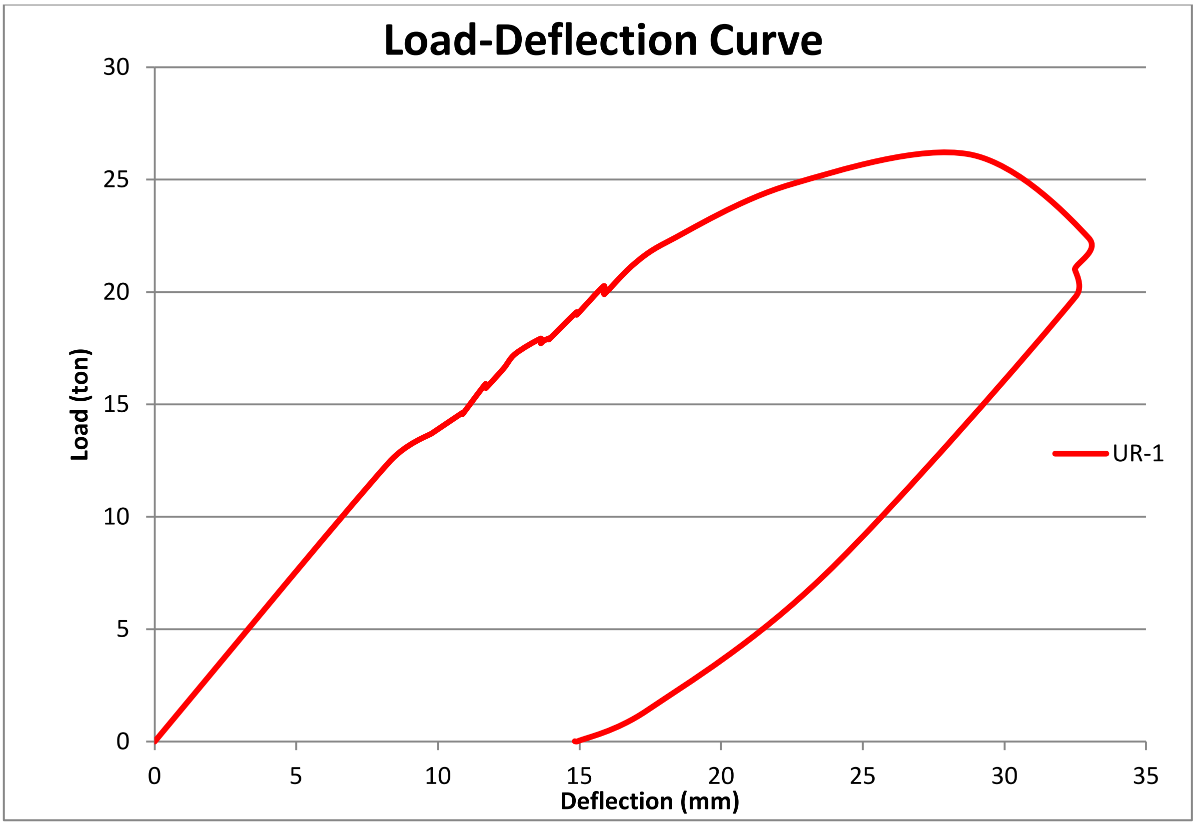


Figure 4.1: Load-Deflection Plot of Specimen UR-1

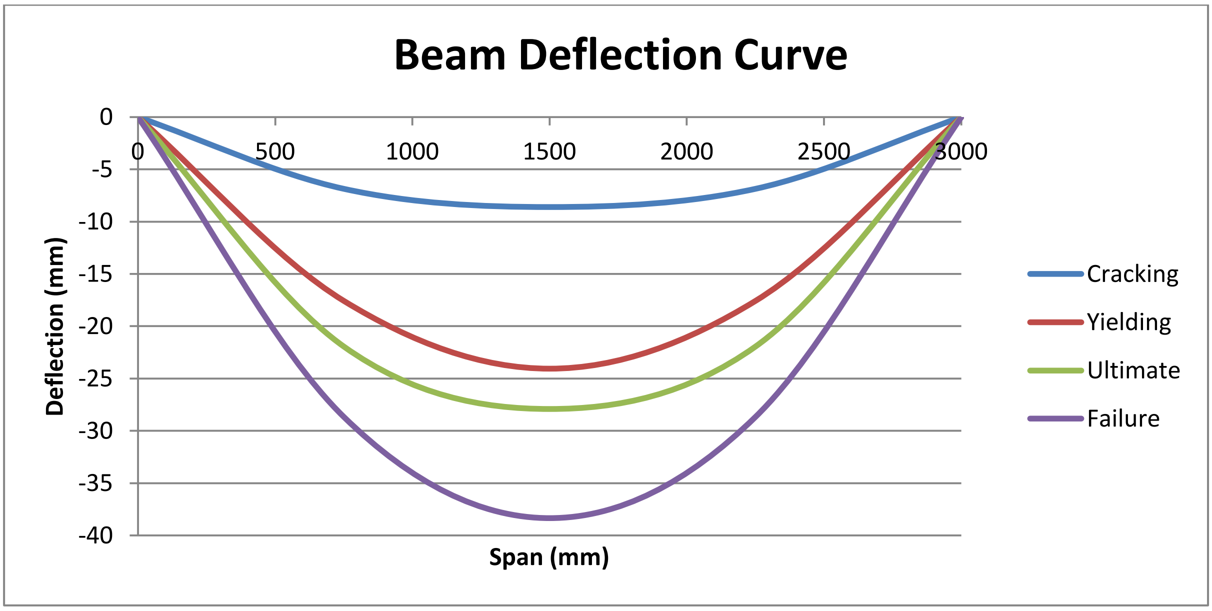


Figure 4.2: Beam Deflection Plot of Specimen UR-1

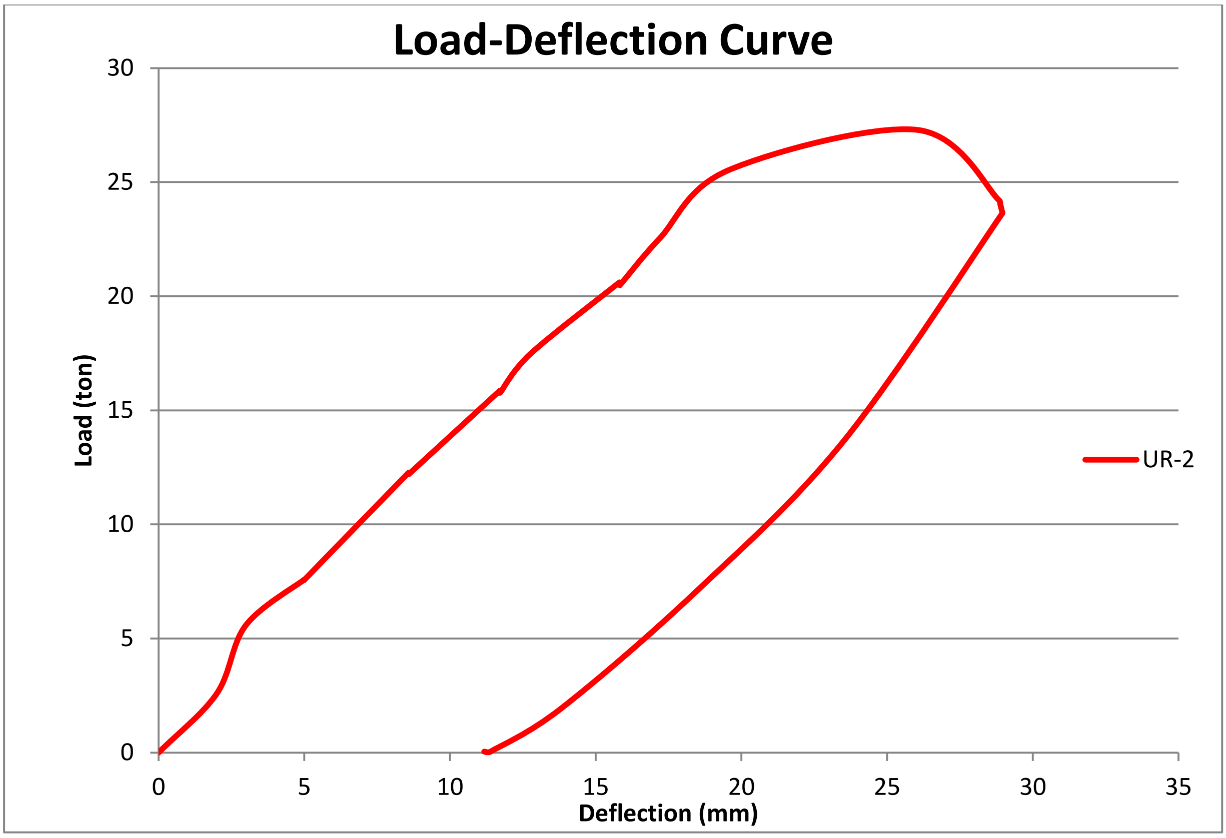


Figure 4.3: Load-Deflection Plot of Specimen UR-2

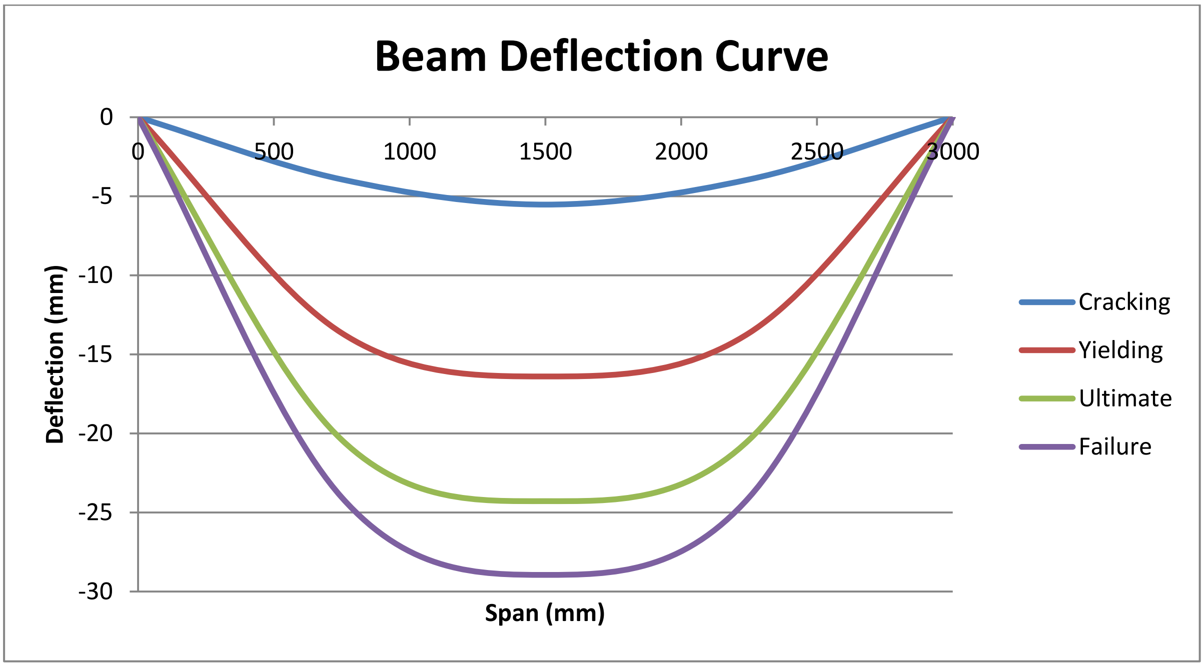


Figure 4.4: Beam Deflection Plot of Specimen UR-2

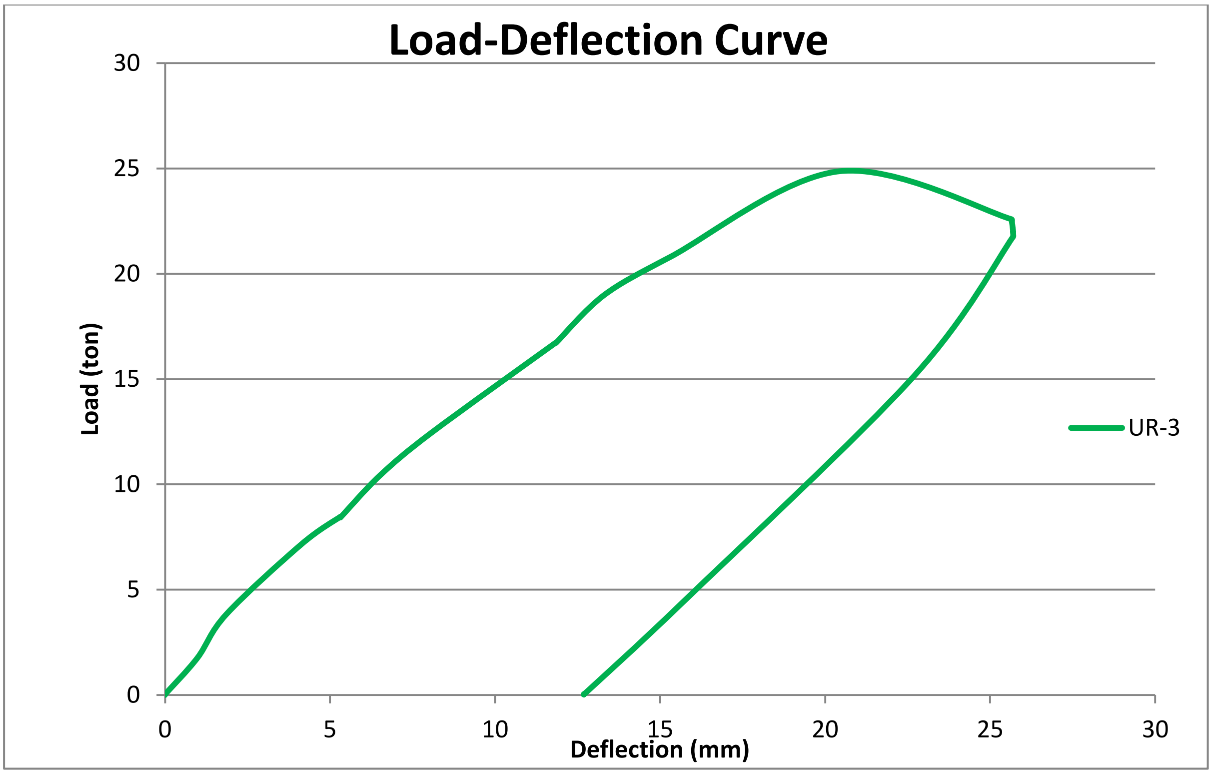


Figure 4.5: Load-Deflection Plot of Specimen UR-3

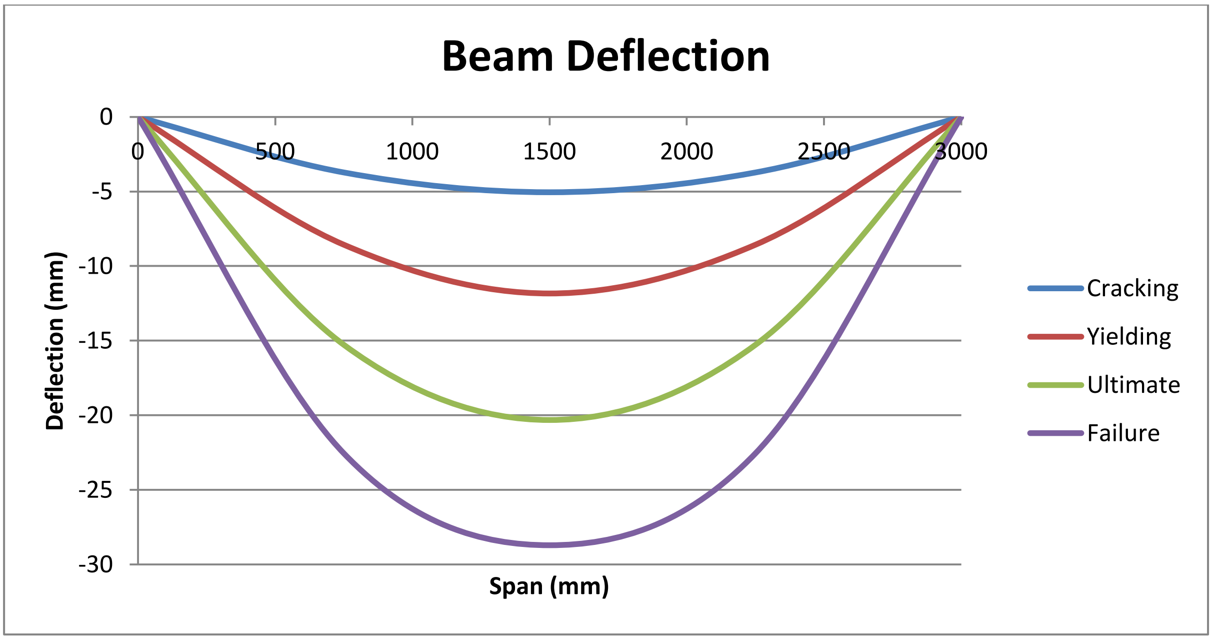


Figure 4.6: Beam Deflection Plot of Specimen UR-3

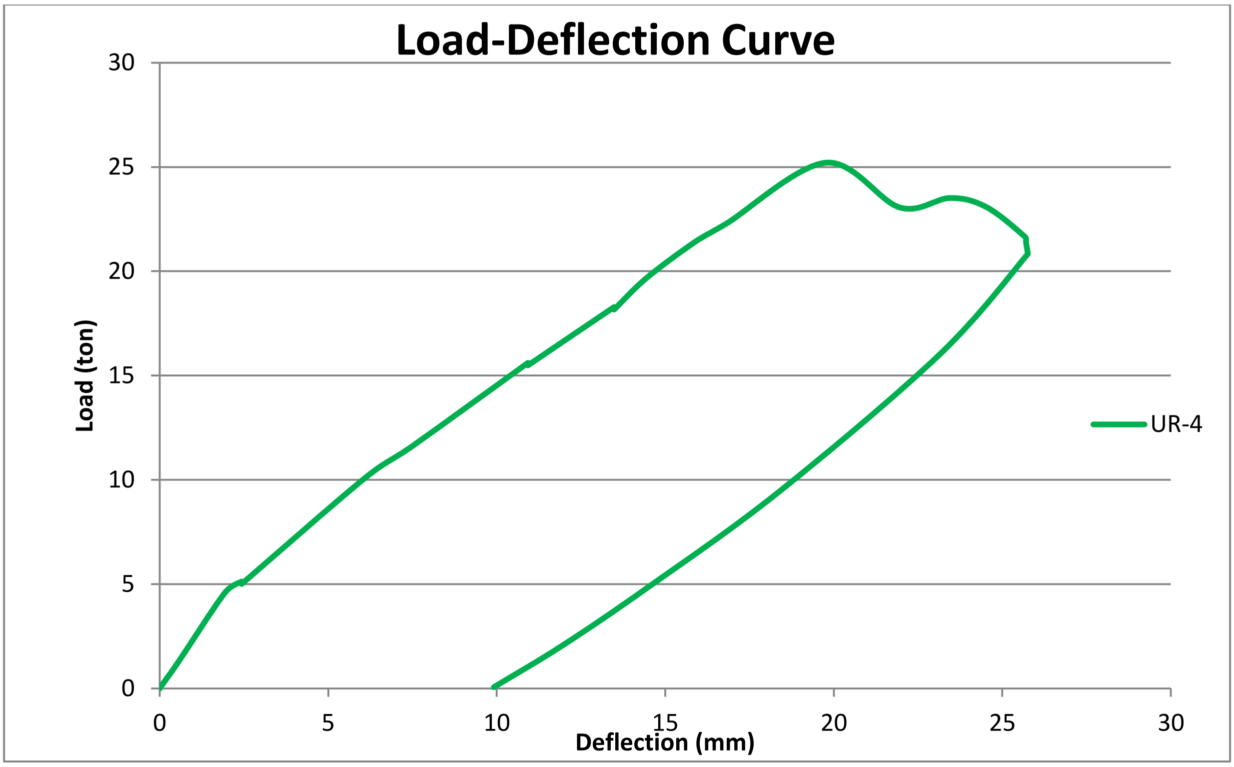


Figure 4.7: Load-Deflection Plot of Specimen UR-4

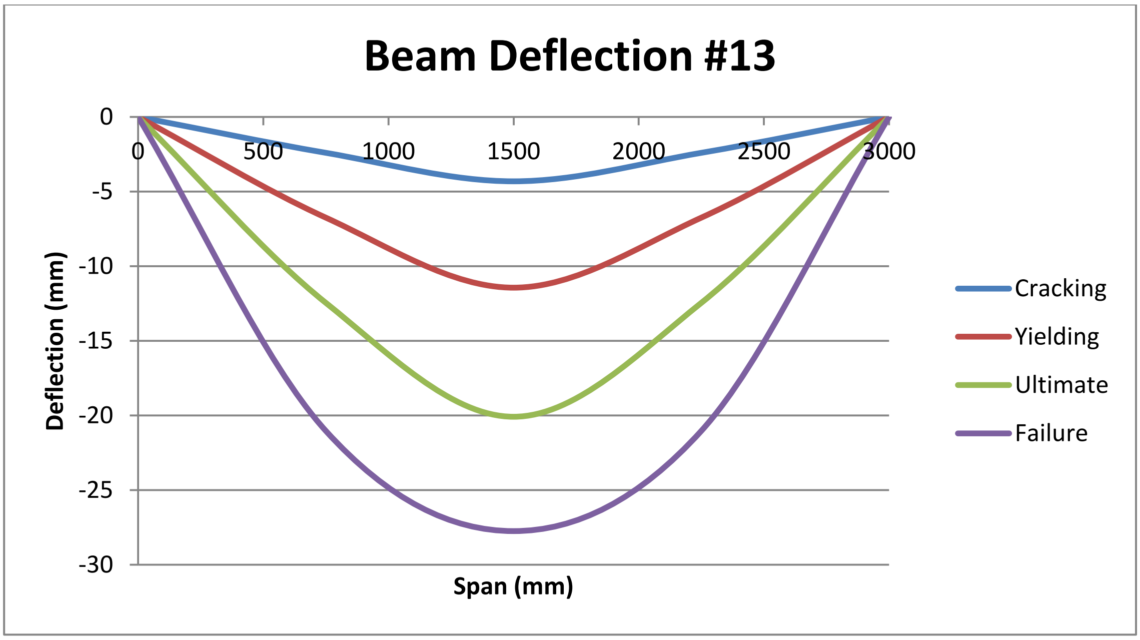


Figure 4.8: Beam Deflection Plot of Specimen UR-4

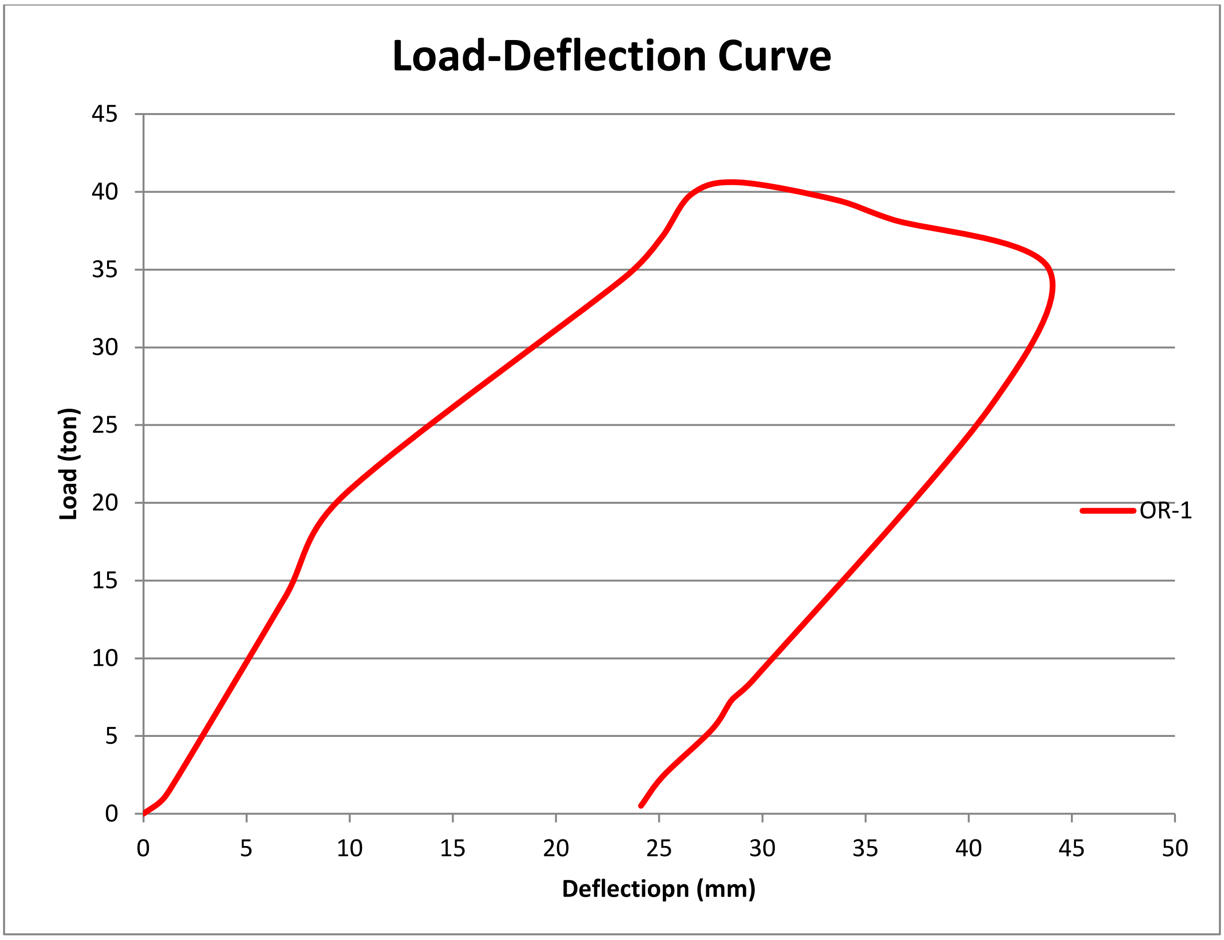


Figure 4.9: Load-Deflection Plot of Specimen OR-1

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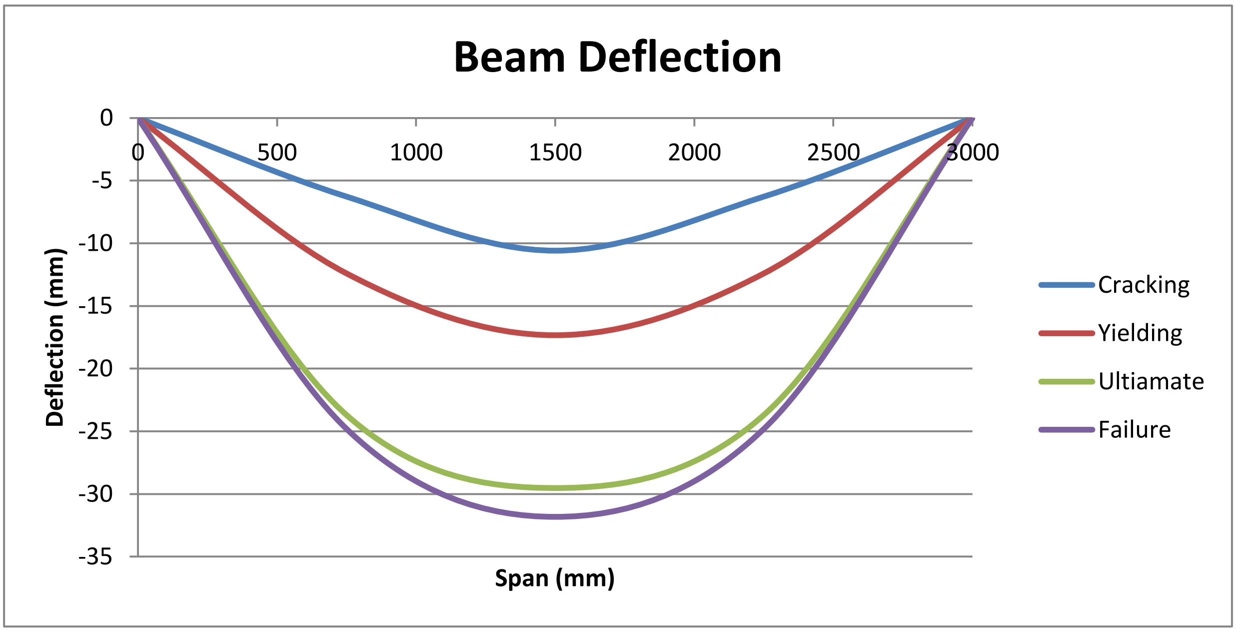

Figure 4.10: Beam Deflection Plot of Specimen OR-1

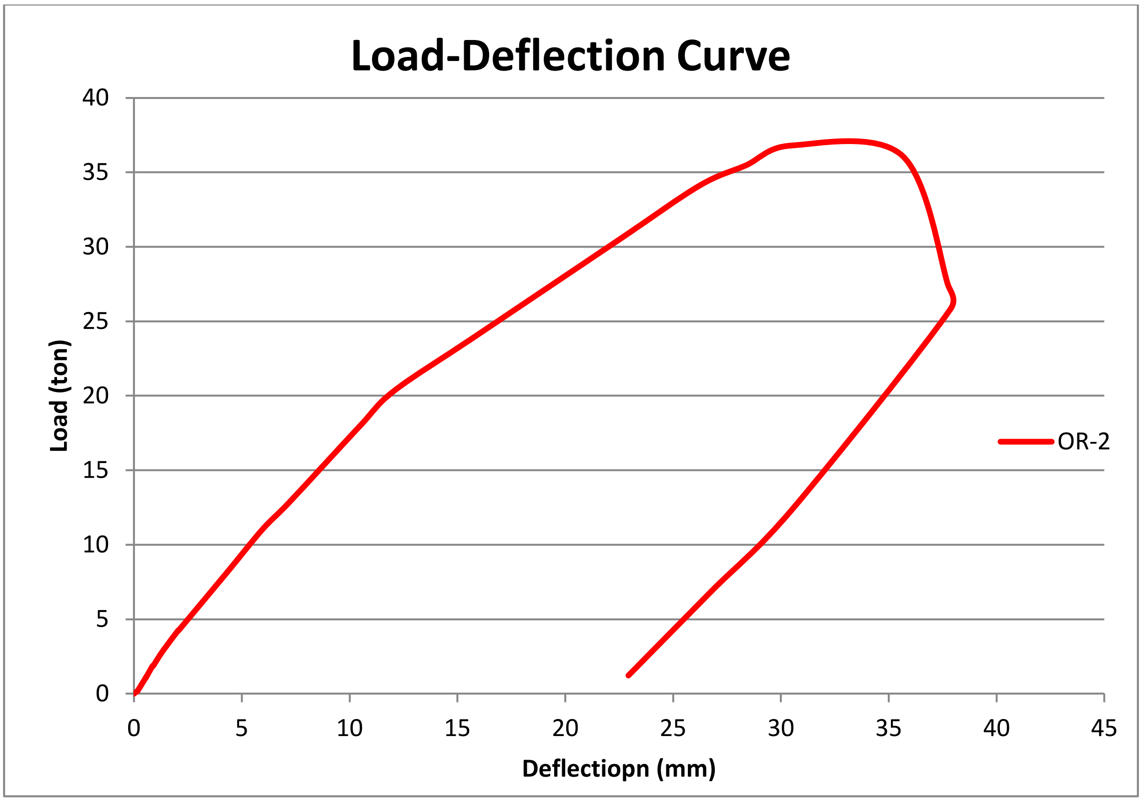

Figure 4.11: Load-Deflection Plot of Specimen OR-2

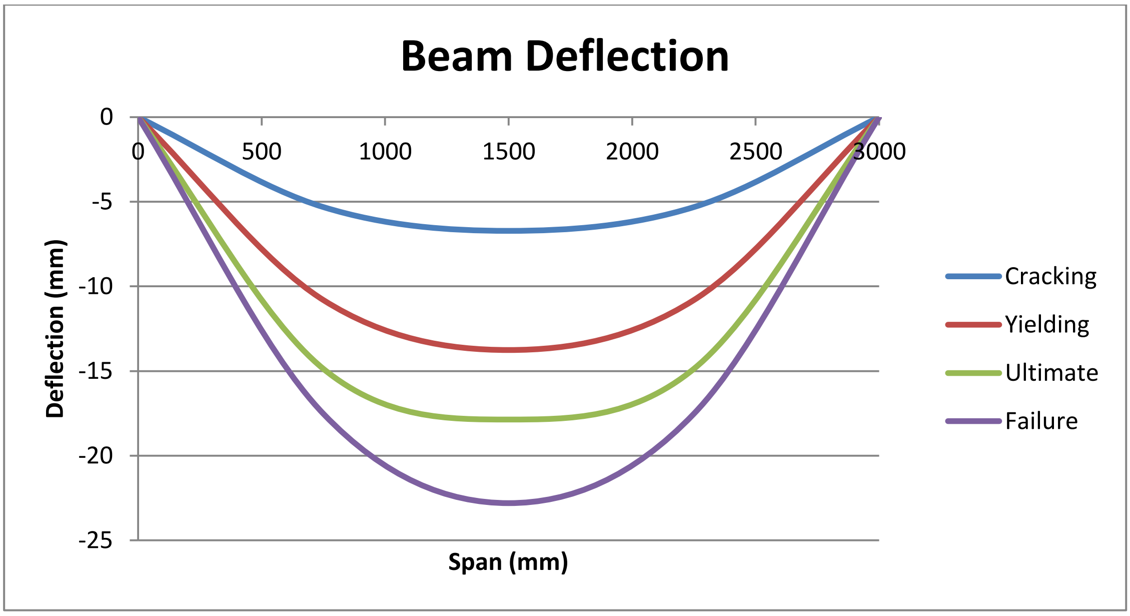

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Figure 4.12: Beam Deflection Plot of Specimen OR-2

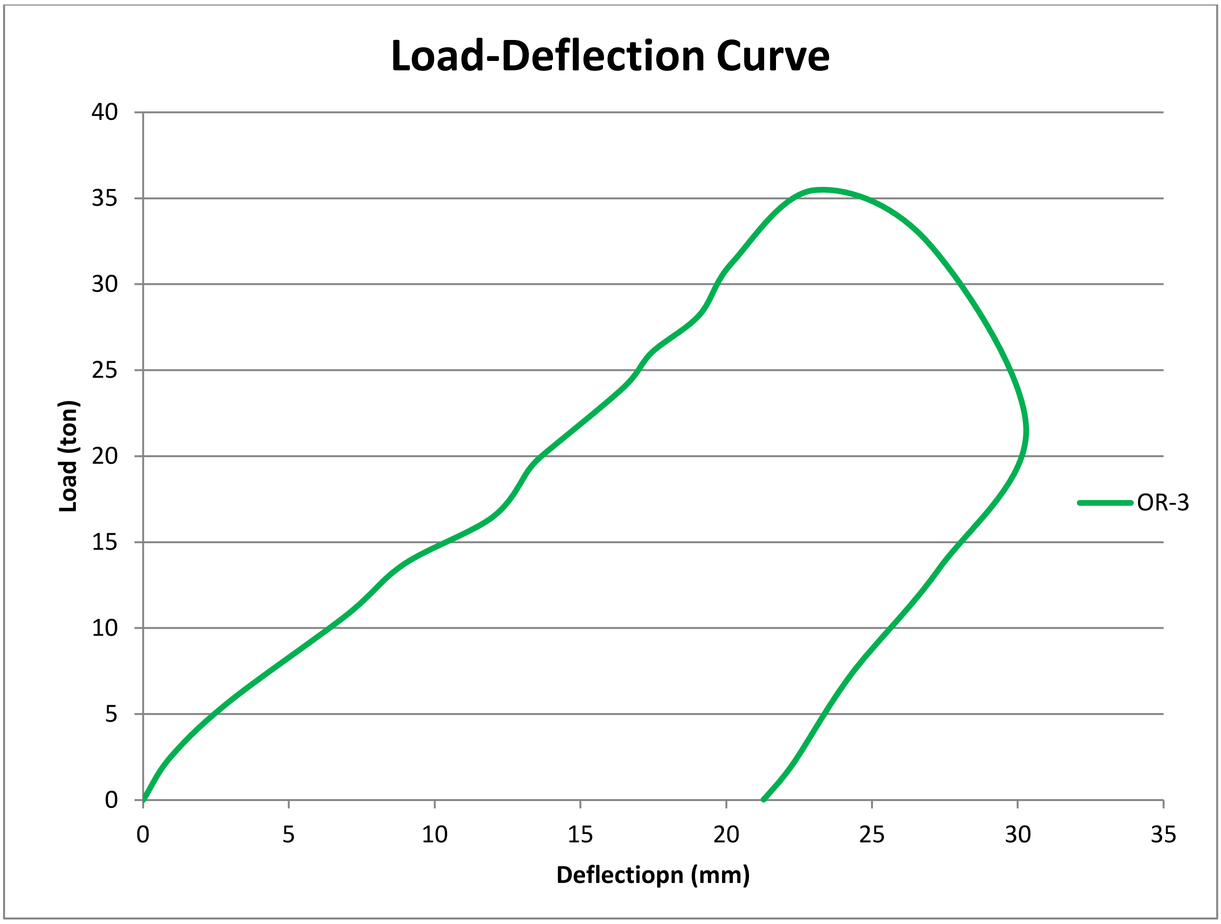

Figure 4.13: Load-Deflection Plot of Specimen OR-3

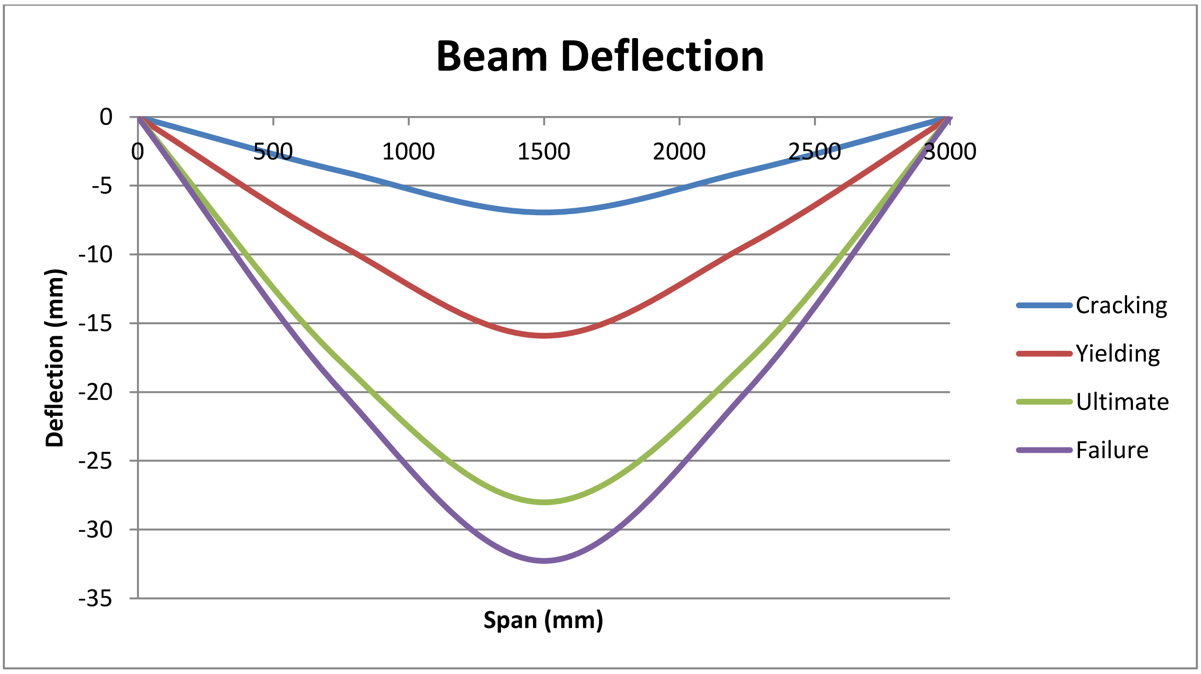

Figure 4.14: Beam Deflection Plot of Specimen OR-3

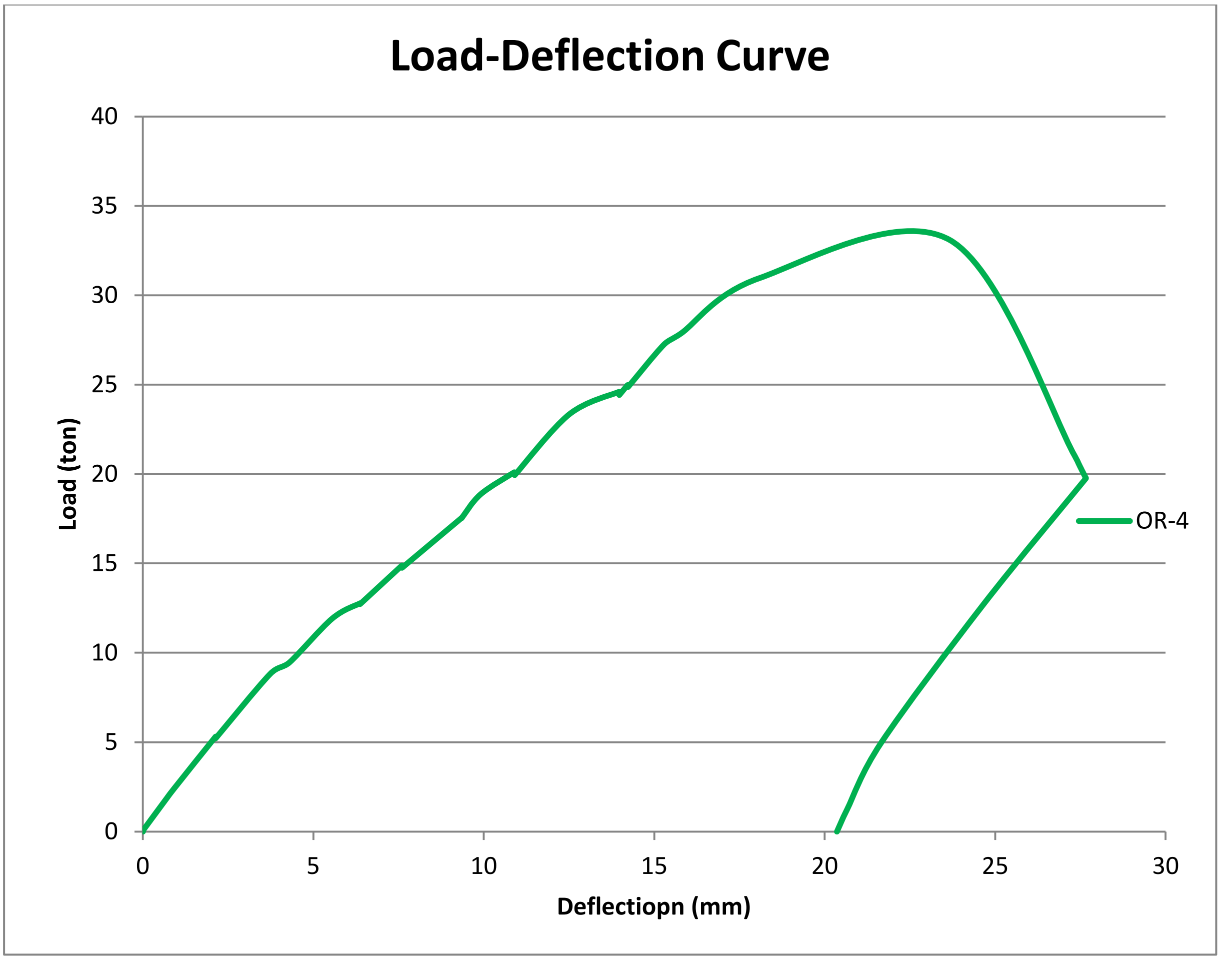

Figure 4.15: Load-Deflection Plot of Specimen OR-4

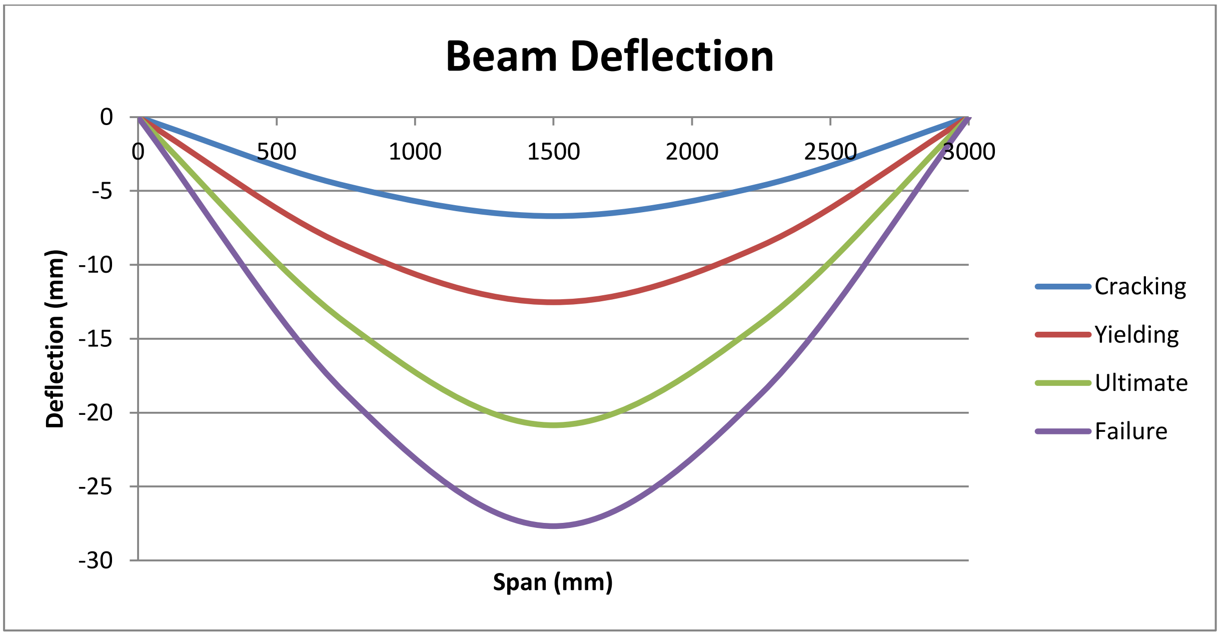

Figure 4.16: Beam Deflection Plot of Specimen OR-4

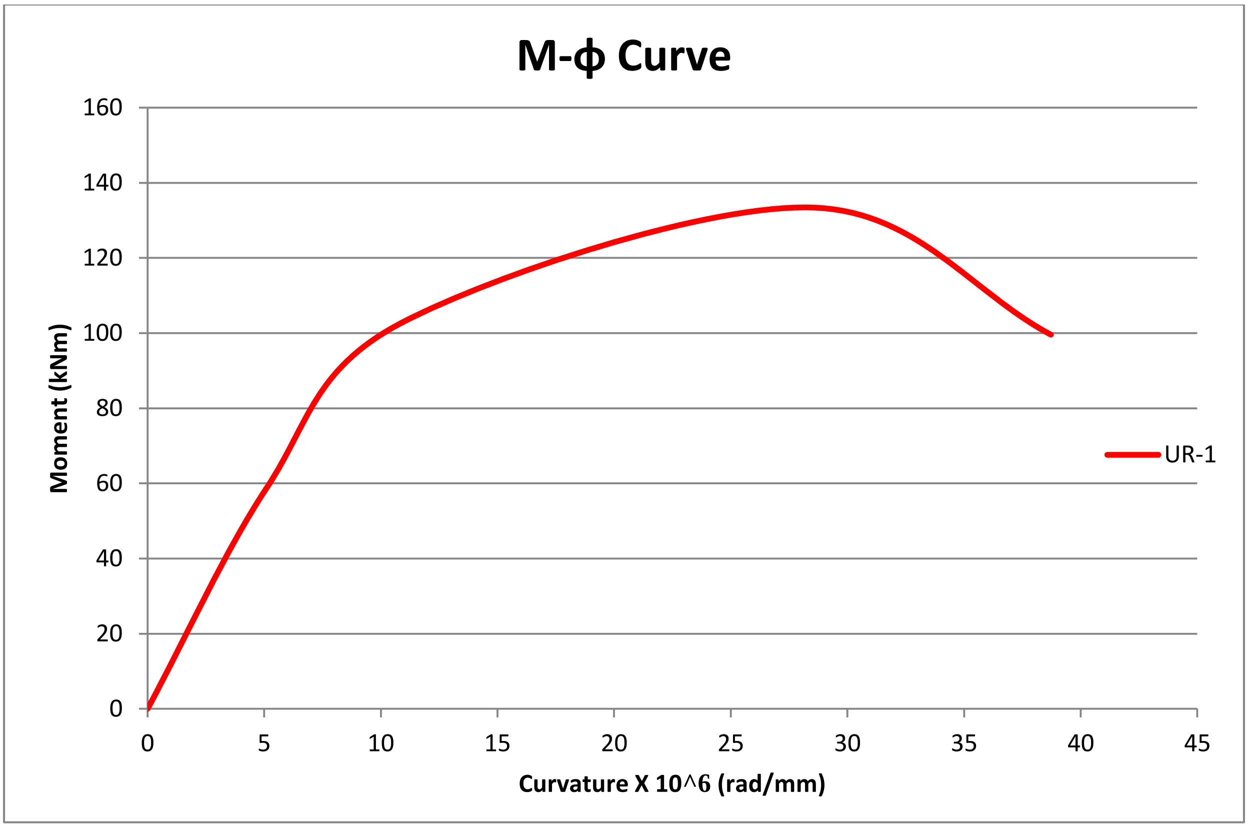

Figure 4.17: Moment-Curvature Plot of Specimen UR-1

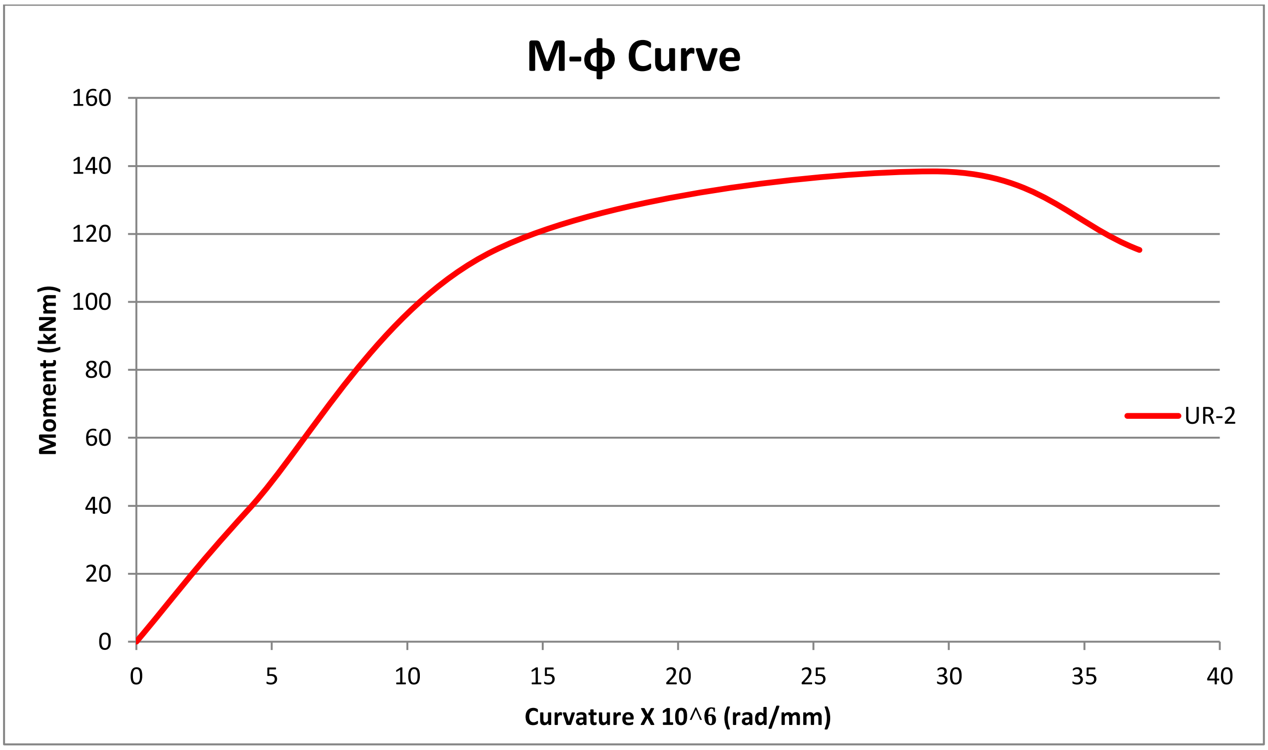

Figure 4.18: Moment-Curvature Plot of Specimen UR-2

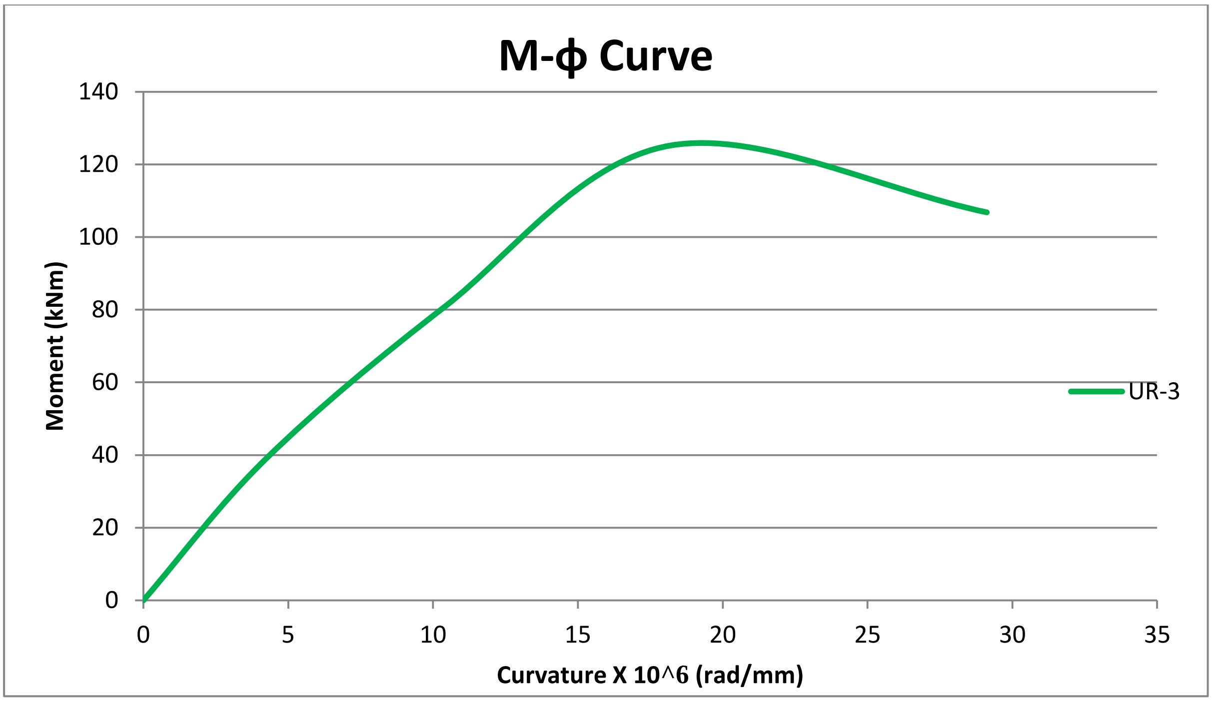

Figure 4.19: Moment-Curvature Plot of Specimen UR-3

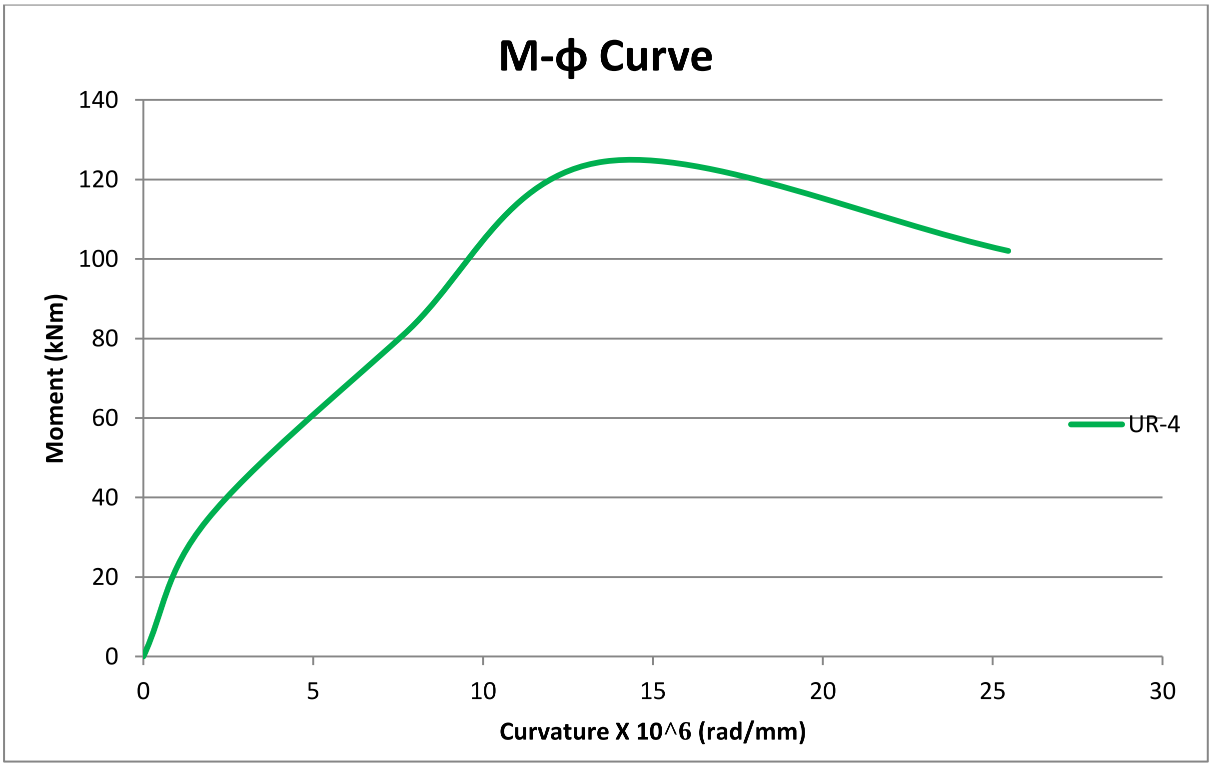

Figure 4.20: Moment-Curvature Plot of Specimen UR-4

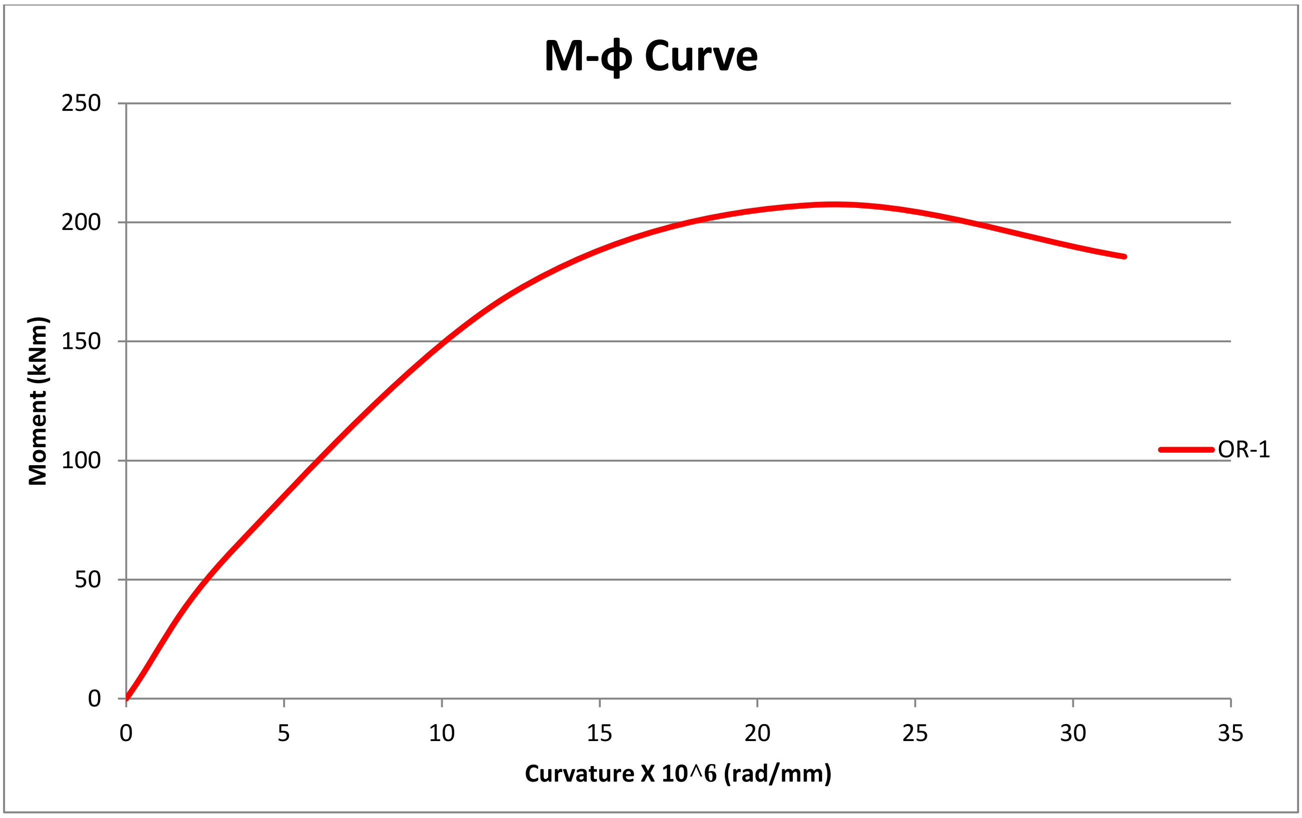

Figure 4.21: Moment-Curvature Plot of Specimen OR-1

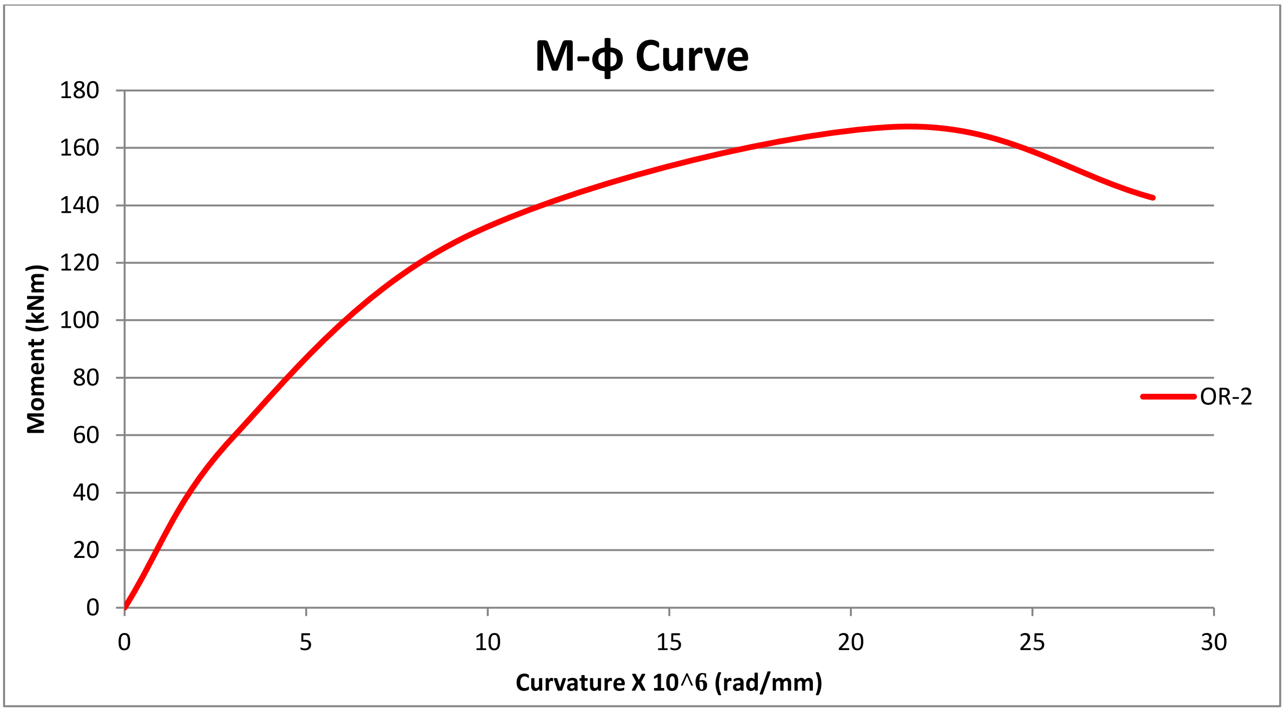

Figure 4.22: Moment-Curvature Plot of Specimen OR-2

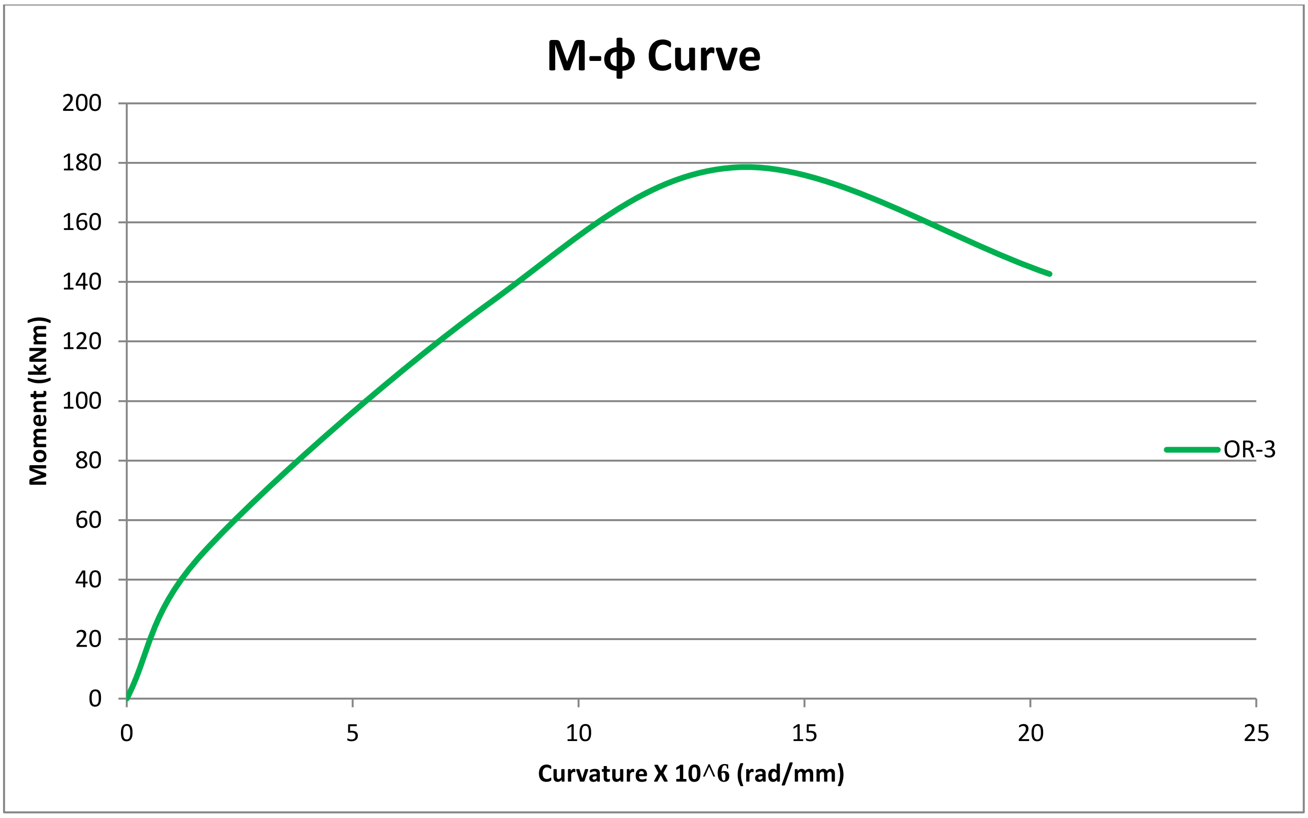

Figure 4.23: Moment-Curvature Plot of Specimen OR-3

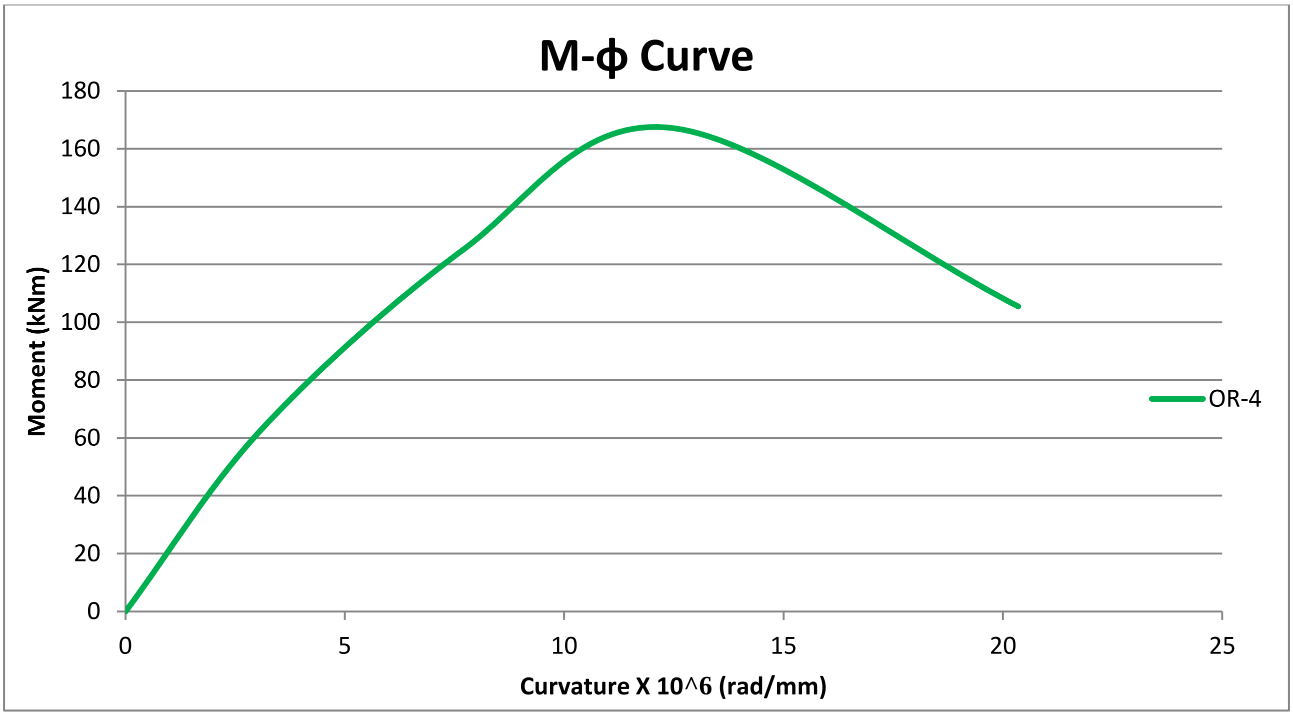

Figure 4.24: Moment-Curvature Plot of Specimen OR-4

COMPARISON CURVE FOR THE $UR_{2.5}$ & $UR_{3.5}$ BEAMS

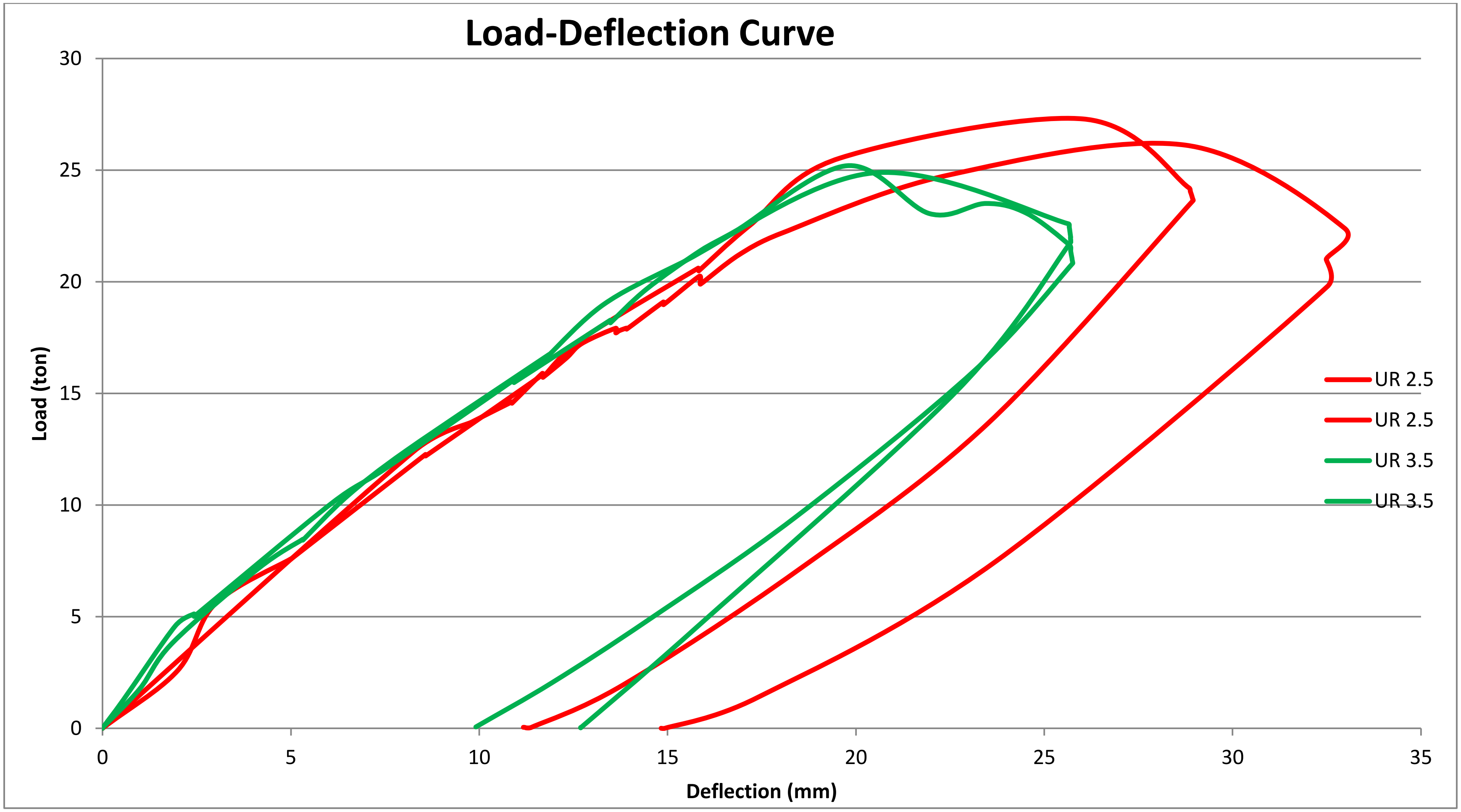

Fig. 5.1: Load-Deflection Graph

COMPARISON CURVE FOR THE $OR_{2.5}$ & $OR_{3.5}$ BEAMS

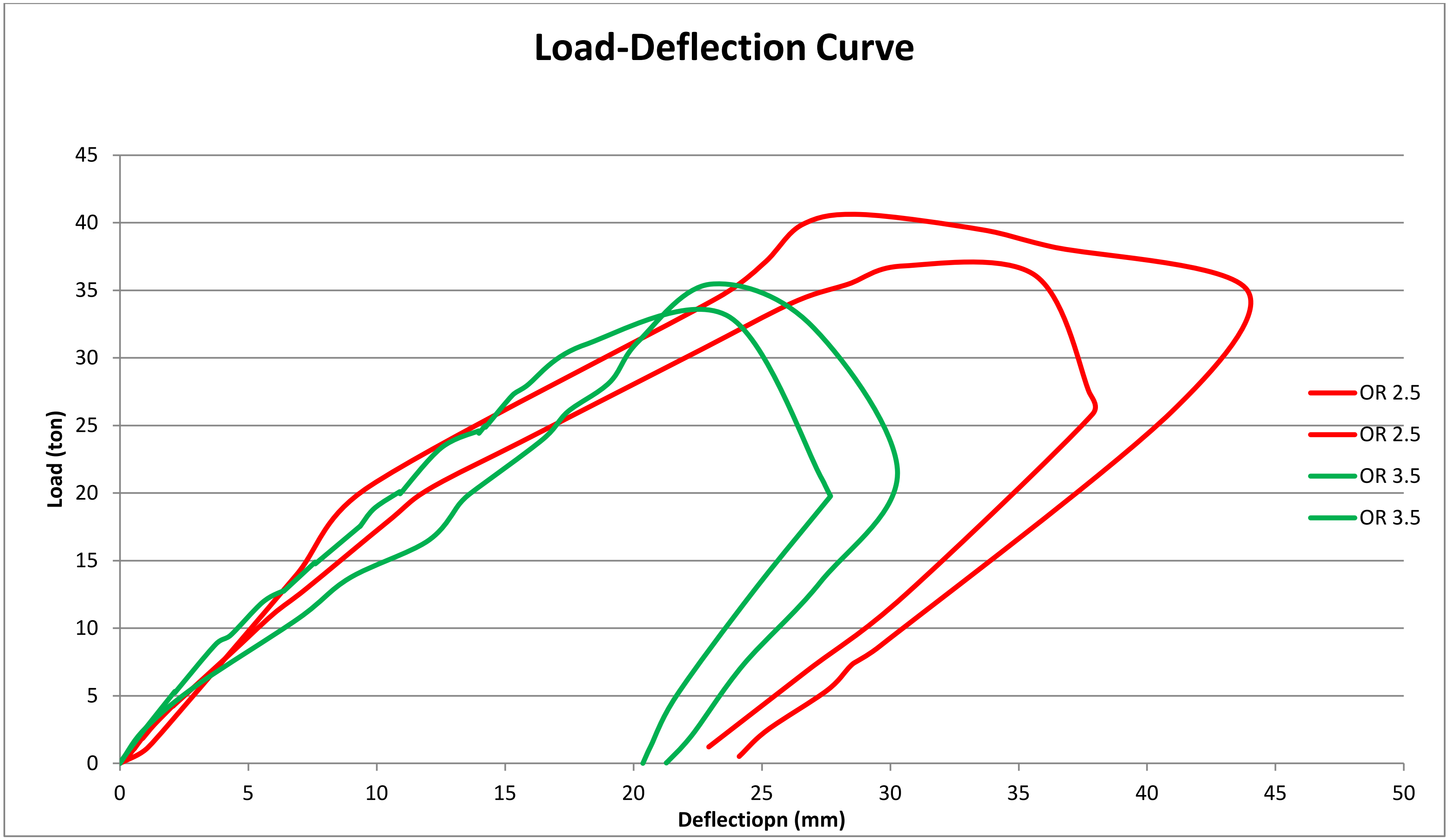

Fig. 5.2: Load-Deflection Graph

COMPARISON CURVE FOR THE UR$_{2.5}$ & UR$_{3.5}$ BEAMS

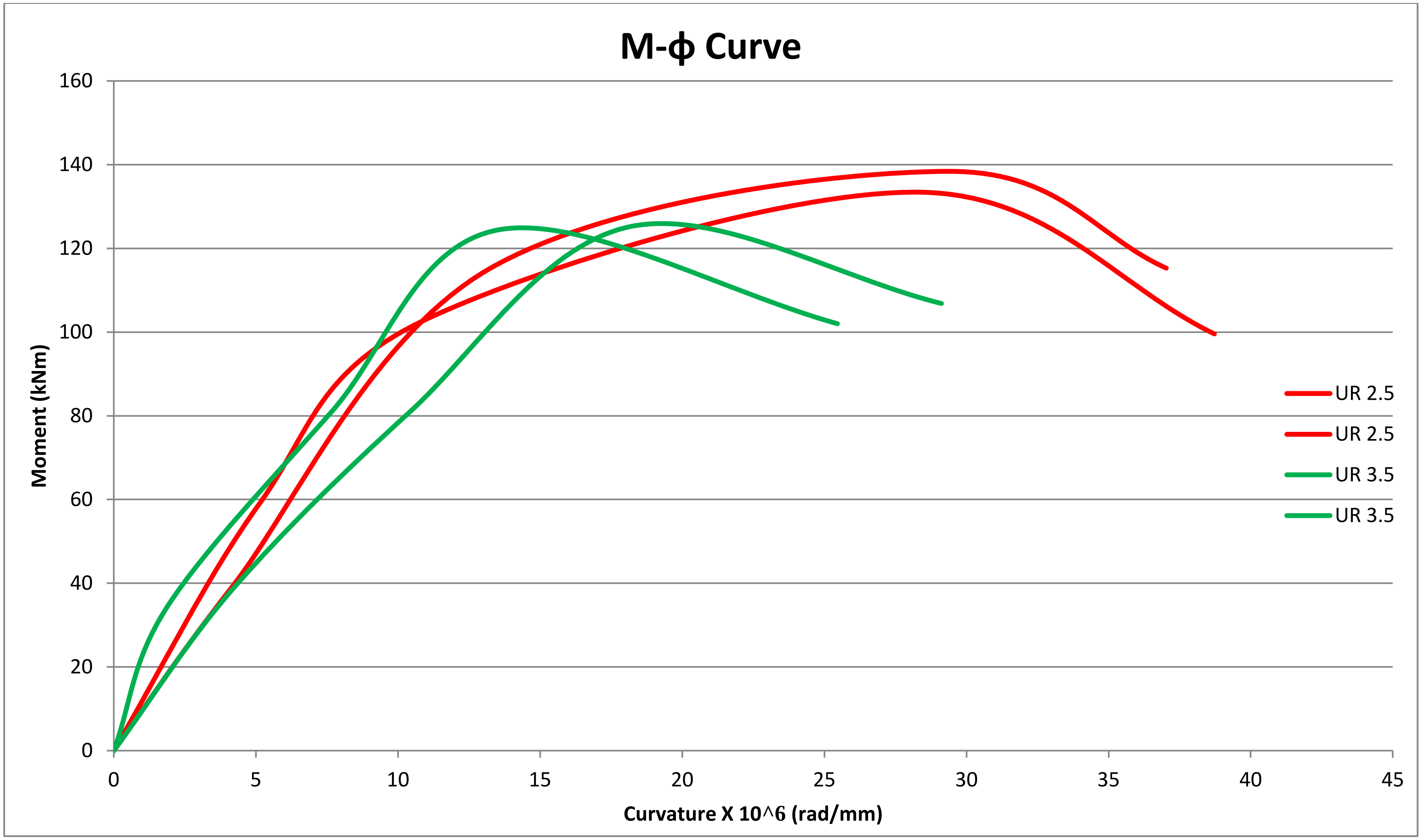

Fig. 5.3: Moment-Curvature Graph

COMPARISON CURVE FOR THE UR$_{2.5}$ & UR$_{3.5}$ BEAMS

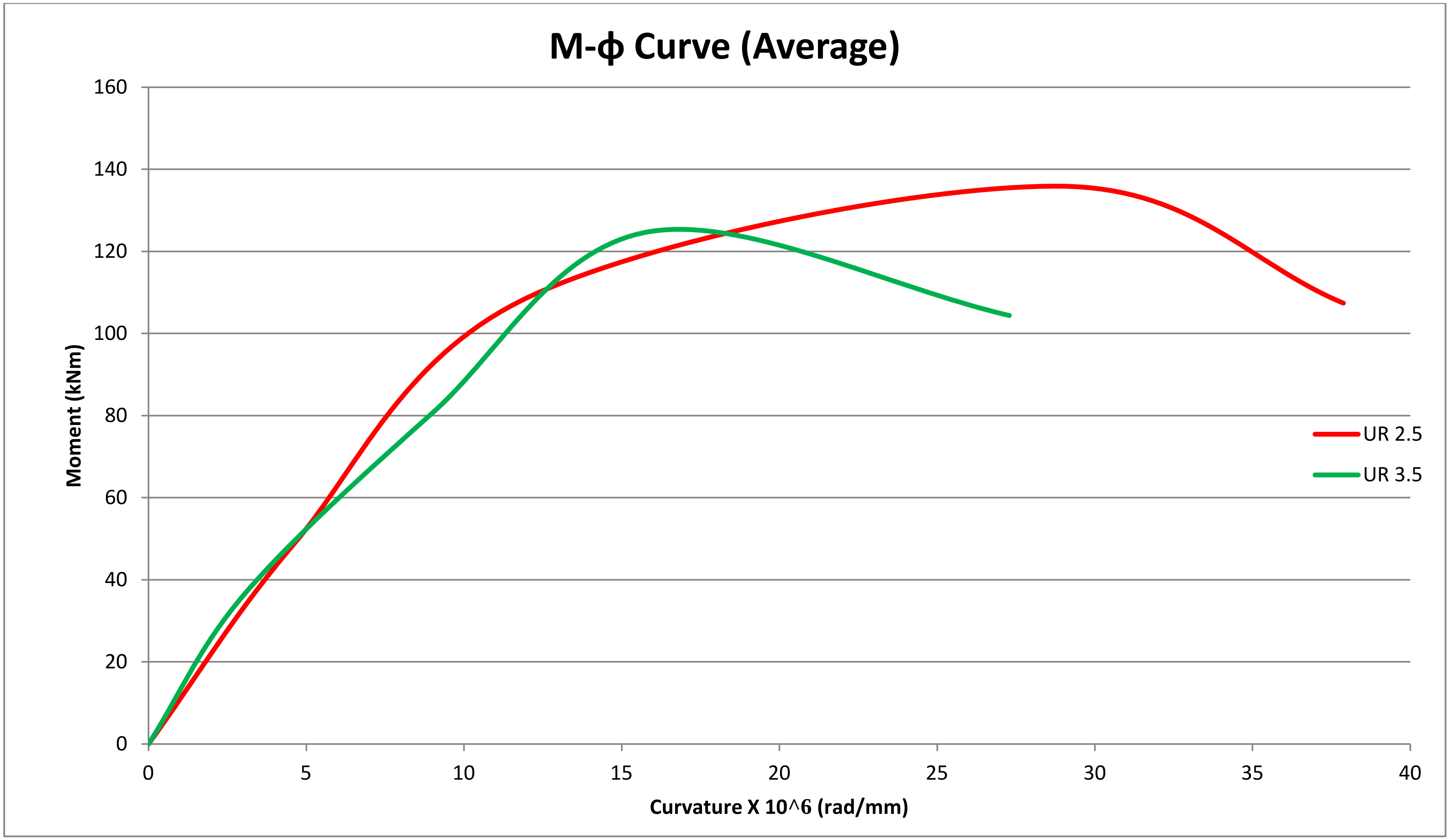

Fig. 5.4: Moment-Curvature Average Graph

COMPARISON CURVE FOR THE $OR_{2.5}$ & $OR_{3.5}$ BEAMS

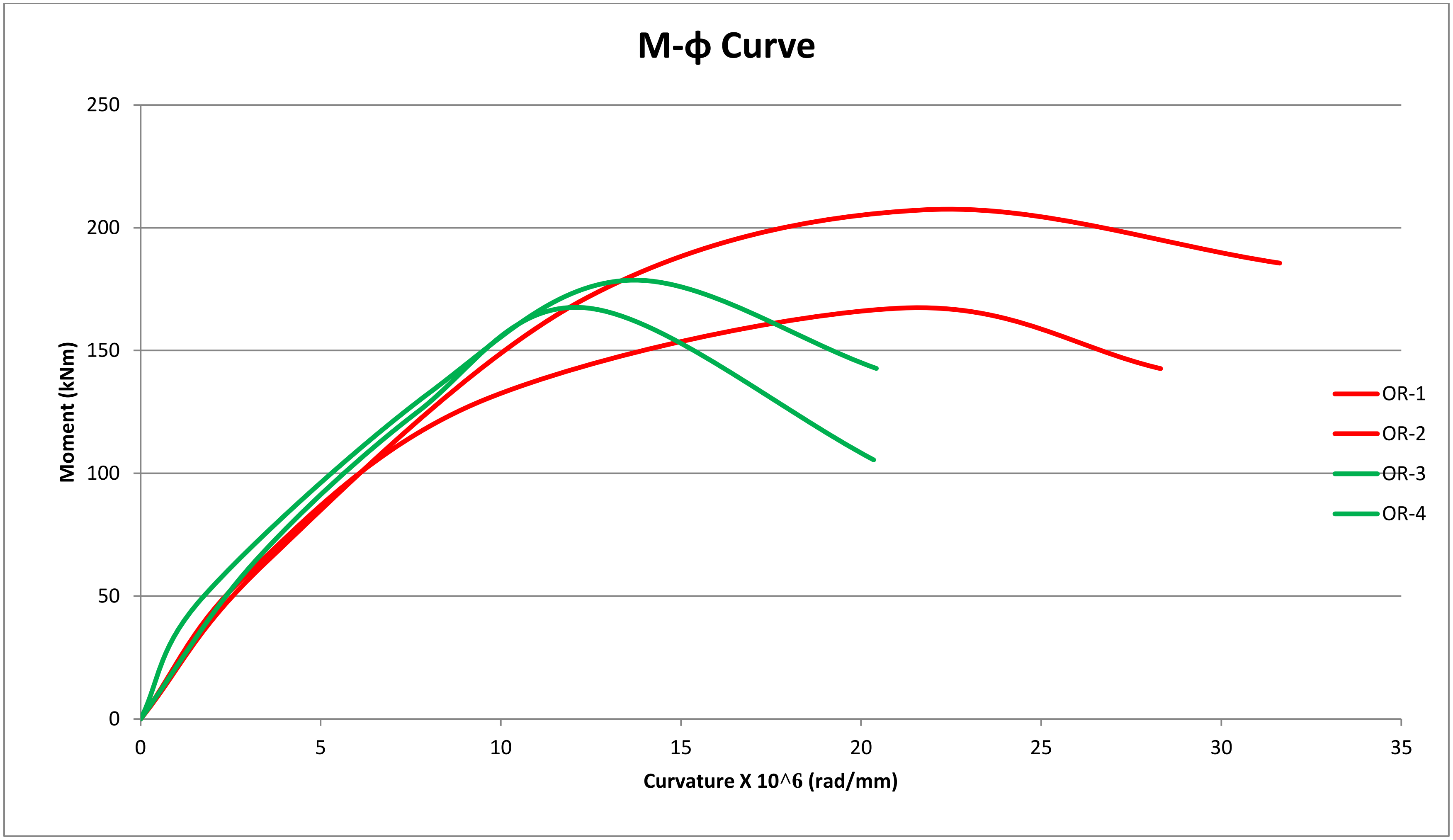

Fig. 5.5: Moment-Curvature Graph

COMPARISON CURVE FOR THE OR$_{2.5}$ & OR$_{3.5}$ BEAMS

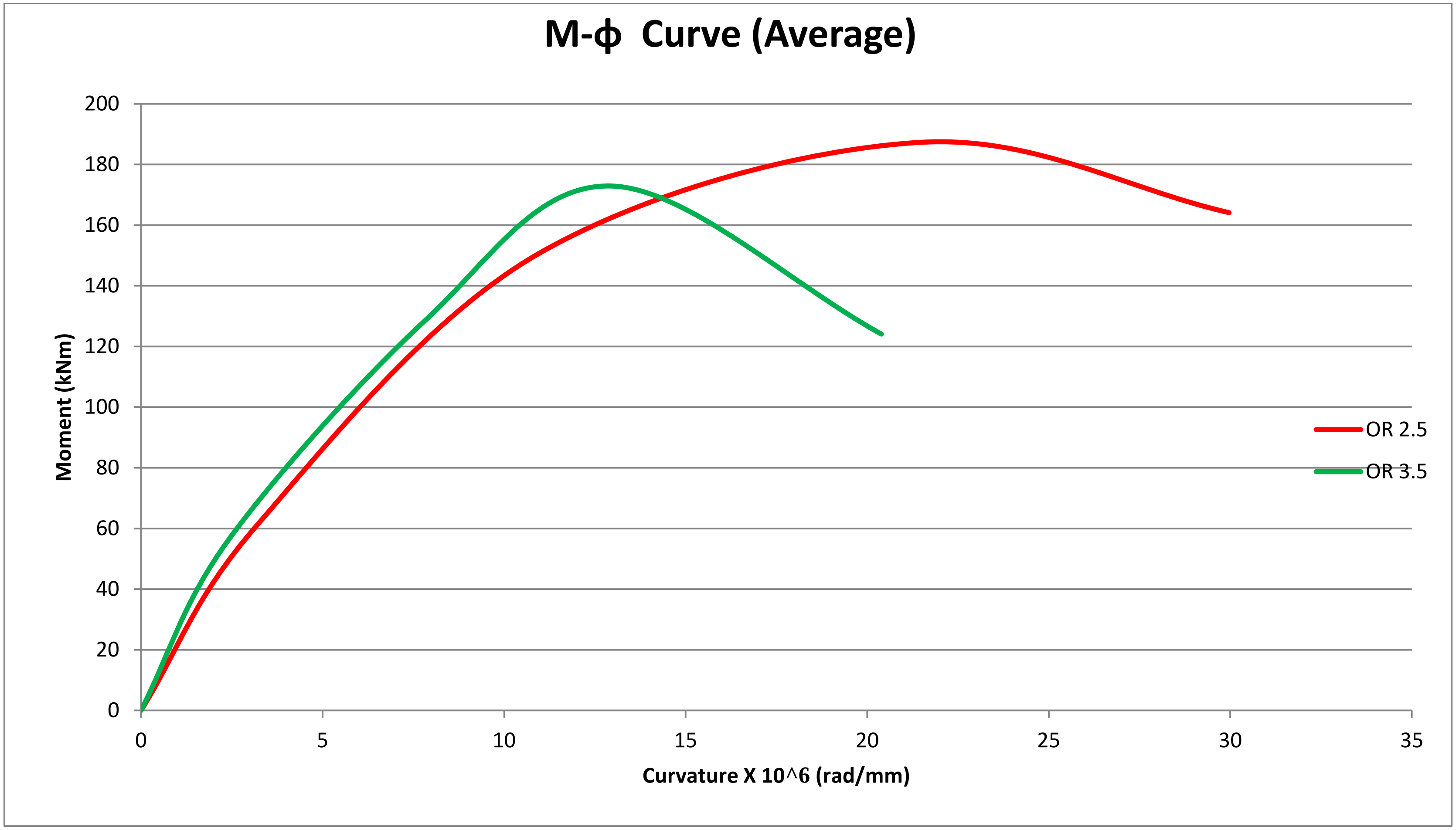

Fig.5.6: Moment-Curvature Graph

COMPARISON BAR CHART FOR THE UR$_{2.5}$ & UR$_{3.5}$ BEAMS

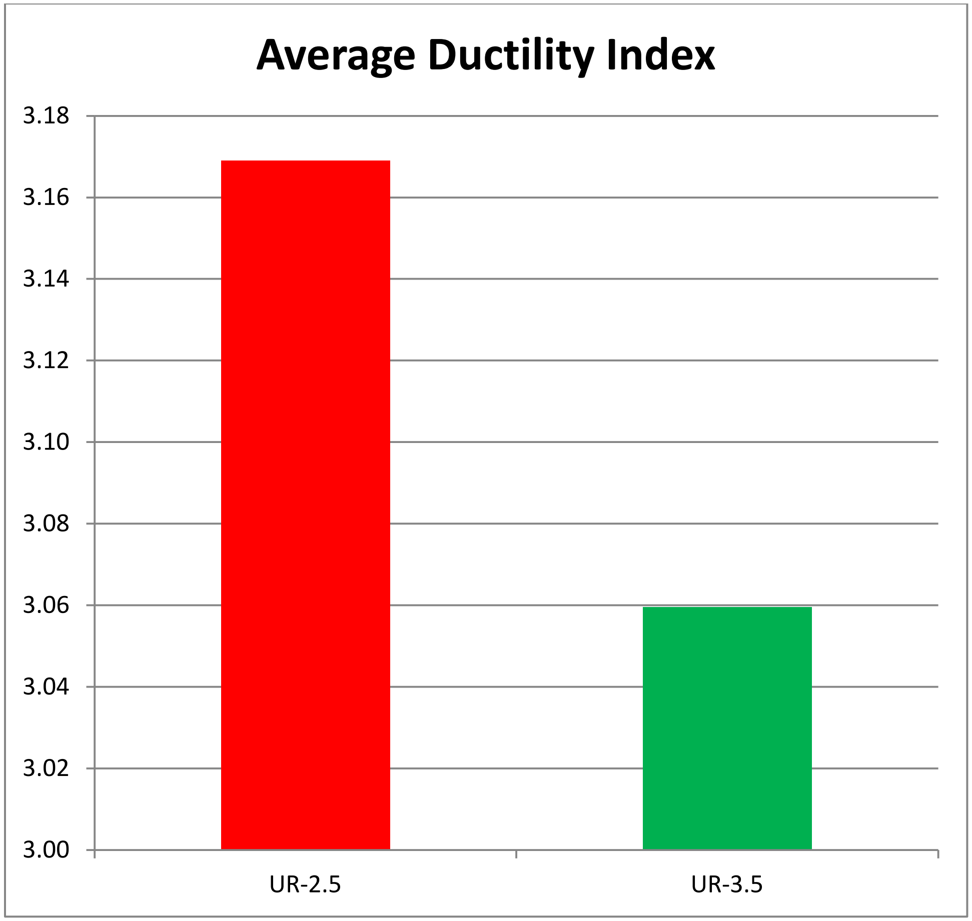

Fig.5.7: Ductility Index Bar Chart

COMPARISON BAR CHART FOR THE OR$_{2.5}$ & OR$_{3.5}$ BEAMS

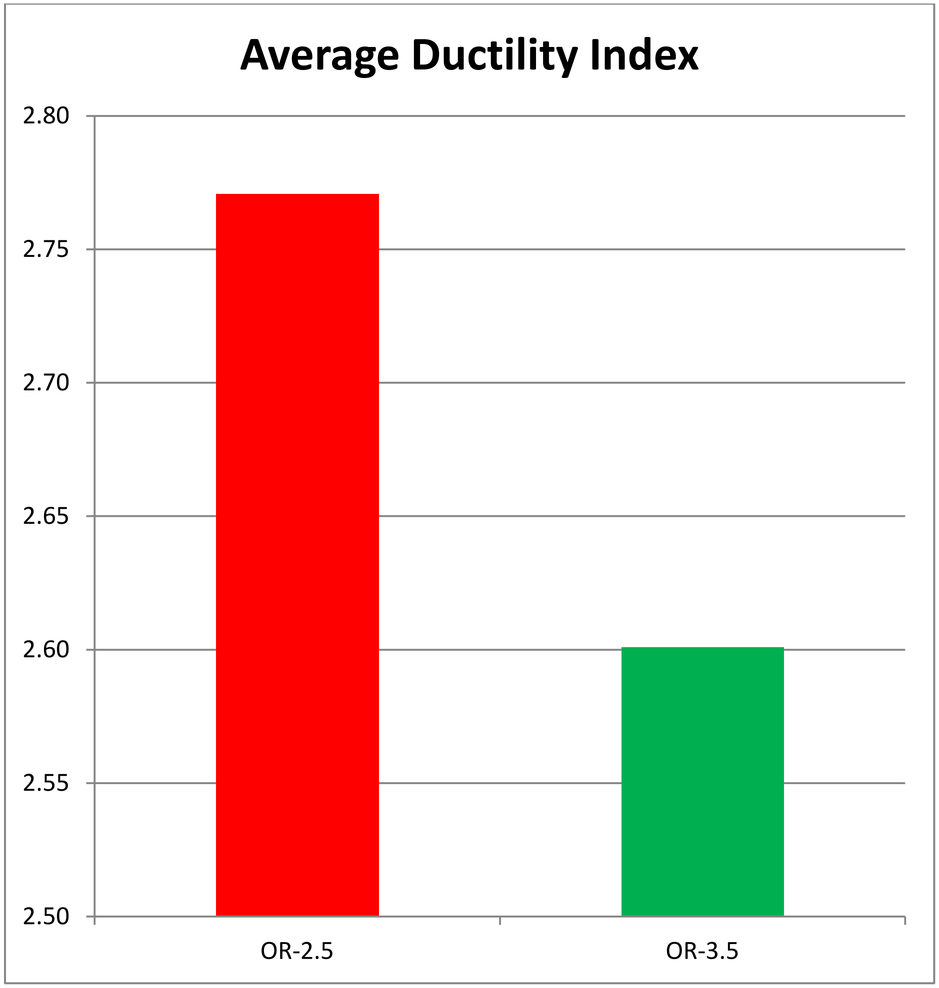

Fig.5.8: Ductility Index Bar Chart