Modified Softened strut and tie model for predicting shear strength of Squat walls with different aspect ratio openings

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(2024)

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Registration Number: 328654

A thesis submitted to the National University of Science and Technology, Islamabad, in partial fulfillment of the requirements for the degree of

MS Structural Engineering

Thesis Supervisor: Dr. Azam Khan

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(2024)

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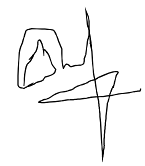

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Abstract

Reinforced concrete squat wall is the prime lateral resisting structure in middle to low rise buildings which experience shear forces. In majority cases, due to occupant needs, ventilation and architectural requirements, openings needs to be provided in these squat walls which can have different shape/aspect ratio as per type and architectural look of buildings. This research considered and looked in to the problem of finding out, which aspect ratio opening is best to worst if provided in squat walls. The approach adopted in this research is an analytical approach, which is modified softened STM modeling in order to know the peak shear strength of various aspect ratio openings in squat wall. The novelty of proposed model is that, the said model incorporates the softening effect by considering a uniform triangular distribution of transverse stresses on struts as a result of tie linked with it and consequently producing a shear strength formula which will produce accurate results for each change in aspect ratio of openings in a wall which was verified by two methods. First experimentally, for that 1:2(B/H) aspect ratio opening squat wall was casted and tested under quasi static lateral loadings and the results were accurate with analytical ones upto 93.32 %. Secondly FEM model of 2:1(B/H) aspect ratio opening squat wall was analyzed in Abaqus software, and the results were accurate upto 93.89 % with analytical results. The validation proved the proposed model valid and accurate for any aspect ratio opening in squat wall. This research will provide benefit to the designers and architects for choosing best shape/aspect ratio of openings in lateral resisting reinforced squat walls.

Key Words: Modified Strut and Tie Model, Squat Wall, Softening Effect, Aspect ratio

ACKNOWLEDGEMENT

"In the name of Allah Almighty”

Most importantly, I extend my heartfelt gratefulness to my mentor & supervisor, Dr. Azam Khan, for his unwavering support, keen interest, and extensive expertise. His invaluable guidance was instrumental throughout the research and writing process of this thesis. His approachable and encouraging demeanor allowed me to discuss my perspectives in depth and address my concerns to my complete satisfaction.

I also wish to acknowledge the significant contributions of many dedicated and supportive colleagues who played a major part in the completion of this study. Also, I am particularly grateful to my friend Arbaz Khan for his steadfast support throughout my academic journey.

Lastly, I express my love and gratefulness to my family for their encouragement and understanding during this pivotal period of my studies.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1 Introduction

1.1 Literature Review

RC structural wall is a Structural feature intended to withstand horizontal forces in buildings that are prone to earth quake and wind effects. It provides stiffness and robust lateral load-bearing capacity to the Structures experiencing significant ground shaking and severe wind pressures. Based on the aspect ratio (Height to length ratio, hw/lw) these reinforced concrete walls are divided in to slender shear walls and lower aspect ratio (typically having hw/lw equal or less than 2)[1] walls named as squat walls.

Squat walls being commonly observed in low heighted construction and at the lower portion of high-rise buildings, such as parking or basement walls)[2] do have perforations or openings in it following the architectural, community and code guidelines which really disturbs the stress distribution in walls also imposing stress concentration near openings. Due to different opening configurations and sizes, similar yet accurate analysis tool isn't obtained till date but several experimentation and modeling techniques are done to evaluate opening effects on squat wall strength, Li et al,. examined and analyzed two set of experiments on squat wall having irregular openings and found out that flanges impressively effects the mode of failure, , Initial structural stiffness, ultimate resistance, and deformation capacity [3], moreover Mastali et al,. Investigated structural response of three reinforced concrete (RC) shear walls with cut-out openings were examined, with a particular emphasis on the effects of increasing the opening eccentricity and exhibited to cyclic loading of reverse nature. The results indicated that the presence of openings and the introduction of eccentricity significantly influenced the failure mode like in this study it was observed that squat wall entered in to the softening attitude at the end of loading stages [4]. Following the opening study in RC walls, progress were made on behavior prediction when Hui and Li analyzed 10 structural wall models(Among these, Yanez tested 6 walls with small aspect ratios, which included 1 solid wall, 3 walls with no regular openings, and 2 walls of regularly shaped openings. Meanwhile, Ali tested 4 slender walls, consisting of 1 solid wall and 3 walls with staggered openings. Both sets of tests were conducted using a reliable FEM program with nonlinear behavior under reversed cyclic loading to simulate their behavior, then these walls under earthquake forces and determining the force transfer mechanism in it[5].Further Wu et al,.[6] also did their research by testing six one third scaled RC squat walls of regular and non-regular openings to investigation the influence of configuration, Size and shape irregularities of openings affecting performance of these structural walls plus they also incorporated date of six perforated rectangular walls tested by Yanez et al,.[7] for evaluating flange effects on these walls. The results obtained were showing that flanges could increase the strength plus it can change the response from ductile in to brittle with a failure mode .Also Kumar et al,. Studied the FEM nonlinear dynamic analysis of Squat shear walls, both perforated and non-perforated walls, attained to the El Centro earthquake at various damping ratios and the results showed that presence of opening imposed sever displacement and concentration of stress adjacent to the opening tip [8]. For improving the perforated walls behavior, different techniques were developed and investigated in the literature including the study conducted by Seki et al,. To experimentally check the influence of two perimeters, named extra reinforcement circled the opening and size of opening of 6 RC wall specimens [9]. Further Salman et al,.[10] and Shirneshan et al,.[11] experimentally analyzed the inclusion of fiber containing reinforced polymers(FRP) in perforated squat wall, the earlier one presented an experimental study on walls strengthened with glass fiber with RC polymer(GFRP) and later one investigated the walls strengthened with different configuration of Carbon fiber having reinforced polymer(CFRP), the results obtained were significantly better in improving the horizontal aligning force and capacity of deformation of walls having openings. Additionally, these perforated walls were practiced to be utilized even after being cracked due to severe lateral loading like Tran et al,. Practiced experimentation to check the results of disturbed RC perforated walls retrofitted by encasing FRP strips or sheets, the repaired walls managed to regain some of their strength, stiffness and dissipated energy to reasonable extent[12] In light of above facts it is clearly understood that effects of opening on behavior of squat wall is experimentally studied with certain perimeters like size of openings, position of openings, additional reinforcement and some techniques to make the performance of these perforated squat wall best. An important perimeter that is still under the candle is an aspect ratio of opening that should be put in to view because opening shape is varied according to the requirements of occupants, code, external environment and purpose of openings (Like door, window, duct etc.). So work needs to be done to evaluate the effects of different aspect ratio openings on these reinforced squat walls and to provide accurate information to the society for careful selection of an opening shape to be fit in their RC structural walls because an aspect ratio is clearly dependent on perforations width and height, basically it shows the perforation shape [13]

RC squat walls due to its higher stiffness fails mainly in shear experiencing brittle failure due to its low height to length ratio. Different failure modes are exhibited with these squat walls when subjected to extreme lateral forces, Squat shaped shear walls can be characterized by various failure modes, including diagonally induced tension, diagonal based compression (web crushing), or shear that slides parallel to the base . Consequently, these walls are primarily designed to resist shear forces. Building codes, practice manuals, guidelines, and existing literature offer several innovative equations for estimating the highest graph based strength of RC concrete. These equations use parameters that are ratio of aspect, lateral steel ratio, up down steel ratio, and force compelling axial effect. To compare and assess the most effective and safe design formulations, Stojadinovic et al. evaluated 5 prophetical equations using test data from hundred and twenty rectangular walls. Including these, the equation proposed by Wood in 1990 provided results closest to the experimental findings.

Furthermore, numerous studies over the past thirty years have investigated the behavior pointing the strength of steel-RC concrete (RC) squat walls experiencing earthquake effects. Considering these studies, two rationally explained models for finding shear needed strength have been developed: 1) the softened-truss model and 2) the STM model. Although both models are same based on physically, they change in their treatment of stress induced distribution within the web of wall. The softened-truss model considers a uniform induced distribution of stress, where each portion of the web adding to shear strength. In contrast, the strut-and-tie model posits that stresses are accumulated in specific regions where failure is likely to occur.

While the softened-truss model has generally yielded good predictions, the assumption of uniform stress distribution is not applicable to low heighted RC structures and conflicts pointing to strain fields observed by Luna et al. (2019) and Devine et al. (2020) for walls of squat nature with aspect ratios (αs) between 0.33 and 0.94. Therefore, the STM method is considered the more reliable analysis and design tool for squat RC walls

[23]. Moreover after the highlighted topics of squat walls having openings originated, the usual analytical, code based and different literature based shear strength formulations were not able to predict the strength accurately and making it dangerous to design these

walls, impacting safety of occupants. Therefore several but very limited Softened Strut and tie models (SSTM) were prepared and validated for RC Squat walls having openings such as Li et al,. [3] studied an existing STM model prepared by Paulay and Priestley (1992)[24] for squat wall having irregular openings and proposed an improved model based on strut and tie after investigating experimental test data of walls with squat nature having not regular openings. The improved model gives major close evaluation for high graph strength of walls with no regular openings. For designing slender reinforced concrete wall having an opening at the base Wallace et al,.[25] Used STM modeling for choosing lateral reinforcement and in the results it was evaluated that narrow ratio of aspect structural walls with perforation at the base shows stable hysteretic behavior and significant ductility. From above literature reference it is cleared that improved strut and tie modeling is utilized for designing squat walls with openings but concerned point is that for every change in configuration and shape of opening different strut and tie models were prepared, there isn't any single model which can carry change in aspect ratio plus arrangement of openings and yet gives results with minimum error. Therefore a single model needs to be developed, which should contain perimeters for accommodating change in aspect ratio plus change in configurations of opening as well and gives satisfactory results.

1.2 Research Significance

Reinforced concrete squat wall is common lateral resisting structure in low rise buildings. Shear failures are mainly observed in these squat walls due to less slenderness. In majority cases, due to occupant needs, ventilation and architectural requirements, openings needs to be provided in these squat walls which can have different shape/aspect ratio as per type and architectural look of buildings. Usual strut and tie models were proposed in the past to evaluate the shear strength of squat wall with and without openings, the softening effect in their model was incorporated by simple rectangular arrangement of transverse stresses on struts as a result of ties, so the accuracy was compromised in each model, similarly every researcher made different models for different opening shape which made the formulation hectic plus lengthy. So this paper proposes a modified softened strut-and-tie model. which produces a novel approach of incorporating a triangular transverse stresses distribution on struts from linked ties, because a tie linked with strut will try to drag strut with it which will produce transverse stresses in struts and in reality it will not be same throughout the length of strut, however it will be more at the extremes and less in middle thus giving triangular distribution, Subsequently any change in aspect ratio of given openings in RC squat wall will be considered and the model will change its formulation by itself thus giving accurate results for every change in walls opening aspect ratio. The proposed model is validated by results of an extensive experimentation of RC squat wall having an opening plus the trend in strength due to different aspect ratio is also validated through numerical simulation of selected walls analyzed in Abaqus software. Additionally some parametric study is also done to gauge the changes in strength with changes in specific parameters. The analytical work presented in this paper makes a substantial contribution to the relatively sparse existing literature on the subject. And can help the society in selecting least disturbing opening shape (defined by aspect ratio) when making a RC squat wall

Chapter 2 : Analytical Methodology

2.1 Shear strength equation for solid squat wall

Firstly solid walls that are mostly utilized for lateral resistance are taken in to light to

Know its shear based strength on subject modified strut and tie procedure. The procedure starts with mathematically finding out equations which can be followed below:

2.1.1 Shear strength equation formulation

For D-region members, complete strength of shear is sum of shear strength provided by each mechanism of force inducing transfer i.e, diagonally produced strut mechanism and truss mechanism as shown in below figures 1 & 2. Total shear effect is equal to The role that concrete plays plus the role of reinforcement in the structure

$$Vn = Vnc + Vw$$

Where $\mathbf{V_{nc}}$ is concrete attributed strength of shear contributed by the diagonally produced strut mechanism and $\mathbf{V_w}$ represents truss mechanism's resulting shear strength, $\mathbf{V_n}$ is shear strength exhibited by the wall of squat nature.

Moreover, Θs is strut inclined angle and is determined as follows:

$$\tan\Theta s = \frac{Hw}{Lw-hb} \quad \textbf{(Θs should not be less than 25 as per ACI)}$$

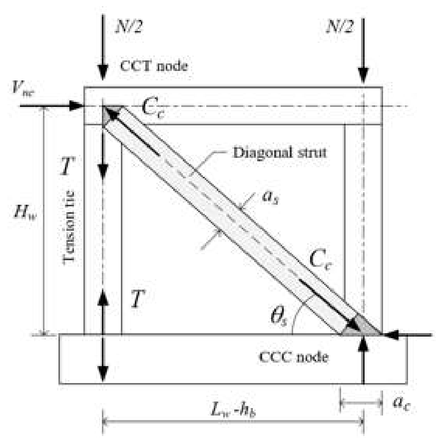


Figure 2. 1: STM Model for Concrete

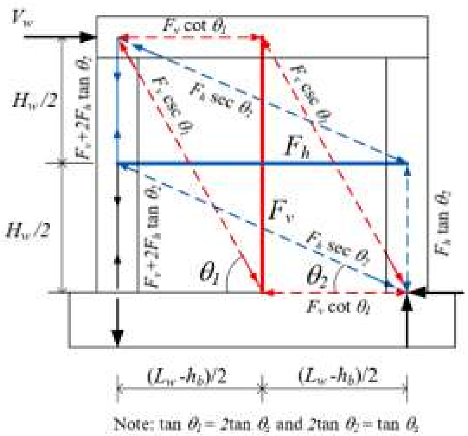


Figure 2. 2: Truss Mechanism for Reinforcement Contribution

In rectangular shaped walls with uniformly distributed up down bars, where hw and lw represent the height cum length of the wall, and hb denotes the length dimension of boundary element, hb is equal to 0.1 lw, which means it is 10% of the wall's length.

2.1.2 By using Diagonal Strut Mechanism

Starting with our proposed concrete strut and tie model, for shear strength formulation we take node C as the crushing node and taking simple strut and tie attacking the node as shown in below figure 3.

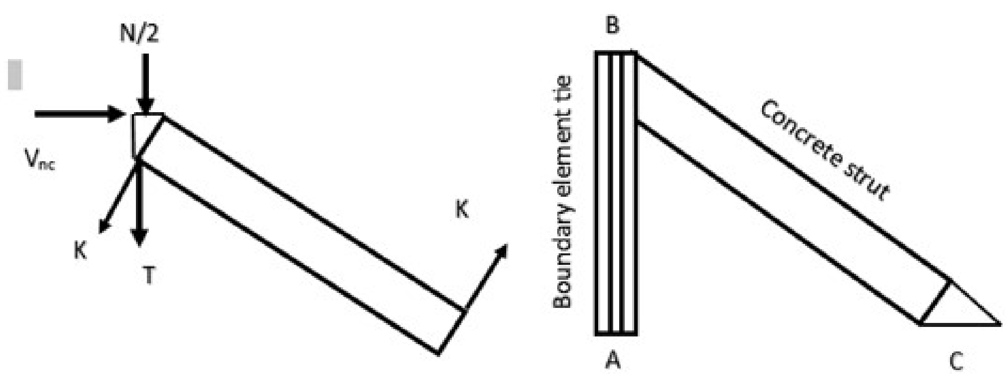


Figure 2. 3 Strut and Tie at Node C

Now taking forces of compressive and tensile nature at Node C shown in figure 2.4 with application of Mohr coulomb equation to start the formulation stage

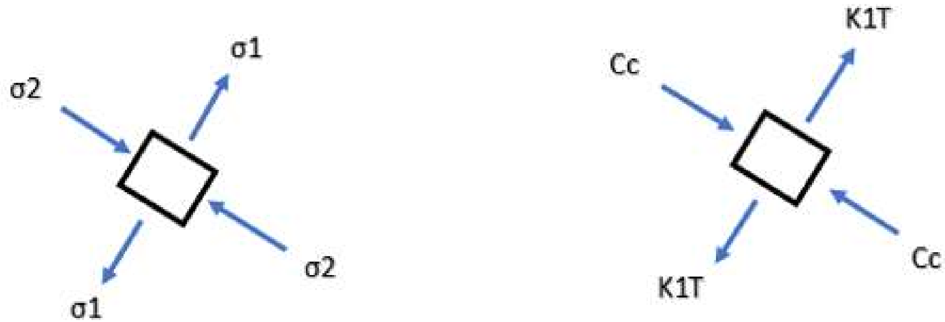


Figure 2. 4: Node C Forces

Figure (2.4) shows concrete strut assumed biaxial state of stresses in at node C which is CCC node (which is bounded by three compressive forces). We resolve above figures using summation of forces along x and y axis as follows:

Principle tensile stress ($\alpha 1$)

$$\boldsymbol{\sigma 1 - k1T = 0}$$

where T is the tension force which has been multiplied with K1- a force distribution factor to represent its distribution of tension throughout the diagonal strut. Hence,

$$\boldsymbol{\sigma 1 = k1T}$$

Principle compressive stress ($\alpha 2$)

$$\boldsymbol{\sigma 2 - Cc = 0}$$

Here Cc is the compressive force generated inside the strut due to application of lateral force V_{nc} which in turn forces the assumed compressive strut to bulge out. Hence,

$$\sigma 2 = Cc$$

K1 stress distribution factor

Tang and Tan considered uniform/ rectangular stress distribution which is inaccurate in comparison to triangular stress distribution which causes both positive and negative stress distribution as shown.

Along the diagonal strut, triangular stress distribution can be assumed to cater for nonlinear changes in stress distribution as we can observe extra confinement at the bottom, in comparison to the top, and Because of the bottom steel's presence. Tan et al.[i] proposed k = 2, k being stress distribution constant, utilizing Force equilibrium is achieved by equating the forces depicted by the triangular stress block to Ts sin$\boldsymbol{\Theta}s$. We do know that though force equilibrium was satisfied at first place, violation of moment equilibrium was observed.

The stress distribution necessary for satisfying both force and moment equilibrium is shown in Fig and the constant for stress distribution, k, can be simultaneously calculated as follows. Although according to the paper, there is a minor 5% difference in strength

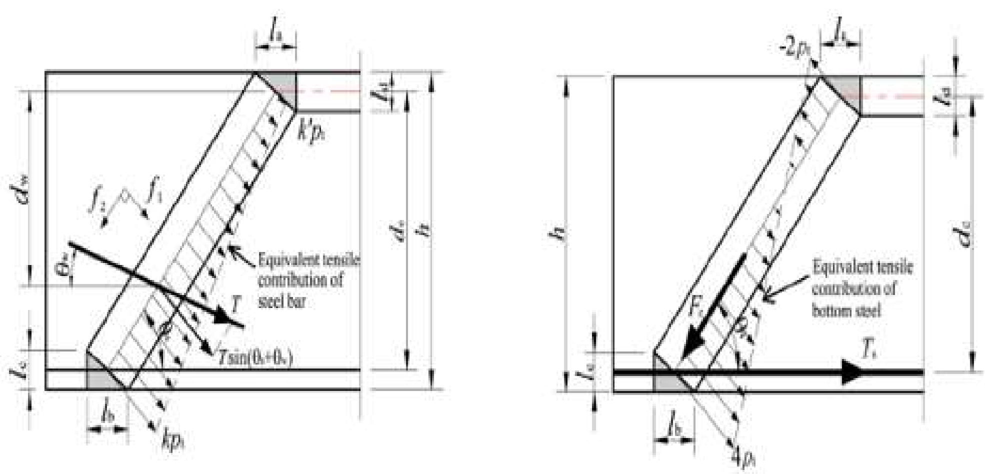


Figure 2. 5 Tensile Stress Distribution

when K is considered 2 instead of 1, yet this effect should be considered for appropriate results.

Applying Mohr- Coulomb failure criteria

For zones of nodes (tension–compression stress state), Ning Zhang, Kang-Hai Tan model [ii] utilizes a failure criterion using Mohr–Columb based theory (Cook and Young 1985) from research paper [i] assumption of Tan et al, as below:

$$\frac{\sigma 1}{f_{tn}} + \frac{\sigma \mathbf{2}}{fc} = \mathbf{1}$$

Where σ2 =< fc keeping in view that bottom node is bounded in both directions(i.e, additional lateral confinement), ftn is strength of tensile nature provided by boundary reinforcement and concrete in σ1 direction and fcr is compressive strength of concrete cylinder, in σ2 direction.

Resolving Cc and T:

From The Given Tringle ABC as shown in previous figure (2.3) note the strut force Cc the shear is horizontal and tensile steel is vertical bring Cc and T in terms of Vnc

$$Cc = \frac{V_{nc}}{Cos\theta_s}$$

$$T = V_{nc} tan\theta_s$$

N was assumed to be slightly sensitive to T considering that low-heighted shear walls tend to endure relatively less axial load ratios (lower the height, lesser the earthquake loads)

V_{nc} is a factor which transforms the compressive force N into equivalent lateral force**.**

$$\upsilon = \frac{f_2}{f'_c} = 1 - \frac{f_1}{f_t} \leqslant 1$$

Tan et al [i] suggests:

It is presumed that the strut has uniform cross-section along its length and is prismatic.

As we know, $\boldsymbol{stress} = \frac{\boldsymbol{force}}{\boldsymbol{Area}}$

$$\boldsymbol{\alpha 2} = \frac{\boldsymbol{Cc}}{\boldsymbol{A}_{\boldsymbol{str}}}$$

&

$$\boldsymbol{\alpha 1} = \frac{\boldsymbol{k1T}}{\boldsymbol{As}}$$

Here As is area of steel of any single boundary element upon which V_{nc} is to be assumed against which shear strength is being determined. Furthermore, A_{str} is the cross-section area of the strut, and it can be represented by the product of wall web and depth of diagonal strut.

$$\boldsymbol{A_{str} = t_w * as}$$

Here, as is the dimension of diagonally induced strut in the depth direction and t_w is thickness of wall web.

Hwang [ ] suggested that, for height of compression zone in flexural effect of a column of elastic nature, the depth of diagonally induced strut as is equal to depth of the flexural compression zone ac, as determined using Paulay and Priestley's (1992) equation (Eq. 4.61, pp. 273-274 of *Seismic Design of Reinforced Concrete and Masonry Buildings* by T. Paulay).

$$\boldsymbol{ac = as = \left(0.25 + 0.85 \frac{N}{A_w fc}\right) l_w}$$

Here A_w= concrete section net area bounded by l_w and t_w, namely shear force directional length of the wall and web thickness, respectively, and $\frac{N}{A_w f'c}$ is the axial load ratio, N being minimum compression force

Putting all the equations to get;

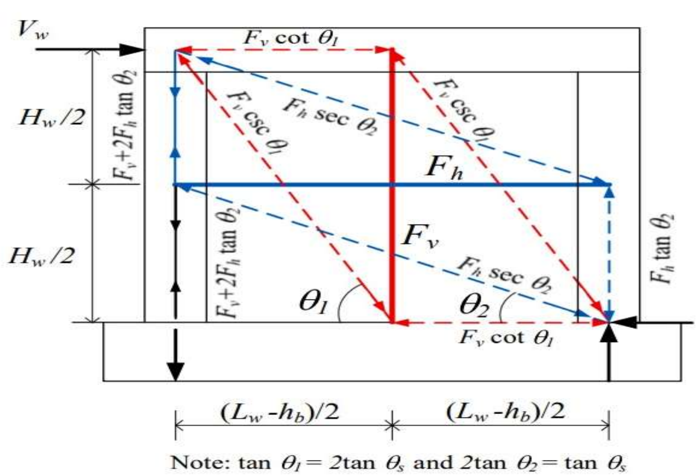
$$\alpha 2 = \frac{V_n}{A_{str}Cos\Theta s}$$

$$\& \quad \alpha 1 = \frac{k1Vntan\Theta s}{As}$$

$$Vnc = \frac{1}{\frac{k1tan\Theta s}{As\, ftn} + \frac{1}{A_{str}Cos\Theta sfc}}$$

2.1.3 Reinforcement Based Truss Mechanism

As the figure below reference of figure shows the truss mechanism based on strength contribution of reinforcement in which the red lines represents trussed and blue lines ties respectively



The truss mechanism constitutes sub trusses in vertical and horizontal directions. The shear strength contributed by these sub trusses is mainly governed by the two ties (vertical and horizontal).

The presence of web reinforcements introduces an extra path of loading for the shiftment of lateral forces in walls of squat nature, potentially enhancing shear resistance beyond what is provided by the diagonal system alone. The horizontal truss mechanism includes one assumed lumped horizontal tie (depicted by a un broken blue line), two vertical members, and two flat struts (shown as dashed blue lines). Conversely, the vertical truss mechanism features one assumed lumped vertical tie (depicted by a unbroken red line), 2 horizontal members, and 2 steep struts (shown as broken red lines).

By force equilibrium, Fx = 0; see eq 1 for vw.. Fh and Fv are yield force determined from Fy of horizontal and vertical reinforcement. See node C in STM model for the following

$$V_w = F_h + 2F_v cot\Theta 1$$

$$V_w = F_h + \left(\frac{2F_v}{tan\Theta 1}\right)$$

$$V_w = F_h + \left(\frac{2F_v}{2tan\Theta s}\right)$$

$$V_w = F_h + F_v cot\Theta s$$

Squat shear walls generally fail in shear therefore the lateral and vertical reinforcement may not get their yield strength. changing equation to:Force = sigma * area, factor multiplied to ensure the shear failure of concrete. Kh and Kv adjusts this force

$$V_w = K_h A_h F_{yt} + K_v A_v f_{yv} Cot\Theta s$$

Using equation (a) and (b) in equation 1:

$$Vn = \frac{\mathbf{1}}{\frac{\boldsymbol{k1tan\Theta s}}{\boldsymbol{Asftn}} + \frac{\mathbf{1}}{\boldsymbol{A_{str}Cos\Theta sfc}}} + \boldsymbol{K_h A_h F_{yt}} + \boldsymbol{K_v A_v f_{yv} Cot\Theta s}$$

Here:

- K1 (Transverse stress distribution factor)
- $\boldsymbol{\Theta s}$ (Depends on Squat wall dimensions)
- A_{be} is equal to $\rho_{be}(b_b x h_b)$
- A_h is equal to $\rho_h(H_w x t_w)$
- A_v is equal to $\rho_v(L_w - h_b)t_w$
- Where $k_h = 0.11$ and kv = 0.19 According to Gulec and Whittaker, and also Ma et al..[iv]
- For K1, From the research of N. Zhang and K. H. Tan,

  Comparing Eqs. (6) and (7), for top and bottom nodal zones, the principal stress of tensile nature can be find out using following factors:

  $k` = 4 - 6 \cdot(d_w / d_c)$

  $k = 6 \cdot d_w / d_c - 2.$

- f_{tn} is the The tensile strength supplied by the concrete in conjunction with the boundary vertical reinforcement. Tang, and Tan et al [iii] suggests:

  That The tensile capacity provided by both longitudinally given reinforcement and the concrete in the elements of boundary

$$Asf_{\text{tn}} = A_{be} f_{ybe} + 0.5\sqrt{fc}\, b_b\, h_b$$

- where fc represents the compressive strength of the concrete
- f_{ybe} is boundary element yielding strength.

- b_b is boundary element thickness and h_b is boundary element width and Abe is boundary element steel area.

  In other words, Asf_{tn} accounts for concrete and boundary element steel tensile strength.

- For w = 0 and $d_w = d_c$ (bottom reinforcement (Fig. 2)), the stress distribution factor is:

  k` = −2 (compression)

  k = 4 (tension). Hence for tensile forces due to bottom reinforcement, take k1=4.

2.1.4 Identification of optimal parameters for the proposed model

The optimum values of K_h and K_v were found to be equal to 0.11 and 0.19 respectively by performing non-linear regression using FIMCON function of MATLAB. Gulec and Whittaker [iv] and For a detailed understanding of parameter optimization, refer to Ma et al. Additionally, the paper "STM Model for Predicting Shear Strength of Squat Walls Under Earthquake Loads" by Panatchai Chetchotisak provides further insights and can be referred to as for the determination of values of the parameters as this procedure was out scope of our Final Year Project.

FIMCON function can be illustrated as follows:

$$A_x =< b$$

$$A_{eq}x = b_{eq}$$

$$min_x\ f(x) \text{ subject to } C(x) =< 0$$

$$C_{eq}(x) =< 0$$

$$Lb =< x =< ub$$

Here $f(x)$ represents the design variable's x, objective function i.e, a, k_h *and* k_v; b and b_{eq} being the vector coefficients of corresponding matrices, A and A_{eq} are coefficient matrices of linear equality and inequality constraints, respectively.

Of the variables *x, ub and lb* are vectors of upper and lower bounds, respectively. C(x) and C_{eq} (x) are nonlinear functions of equality and inequality constraints.

2.2 Shear Strength Equation for Squat Wall with Openings

2.2.1 Finite Element Analysis

For subject research findings such as shear strength prediction for squat walls with openings the first step taken is Finite element approach to analyzing squat walls with openings to get stress contours or stress flow which is used for identifying the possible

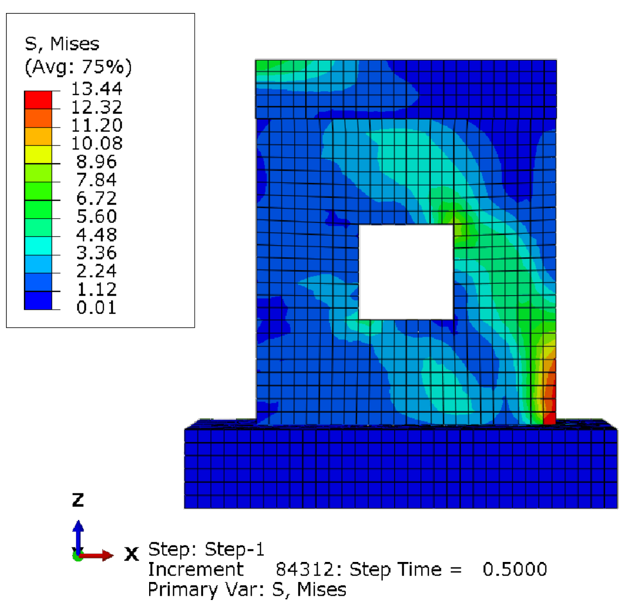


Figure 2. 6: Finite Element Analysis of Squat wall with openings

Position of struts and ties in perforated squat wall. Utilizing the above FEM analyzed perforated squat wall plus literature based study, three strut and tie models (alpha, beta and gamma) (Figure 2.7). Were proposed. For obtaining one yet most accurate strut and tie model, trial and error is performed on a predefined flow chart described in figure 2.8. Trial and error subjects to obtain the peak shear load after formulation of each model and comparing it with FEM analyzed perforated walls results (Table 2.1),

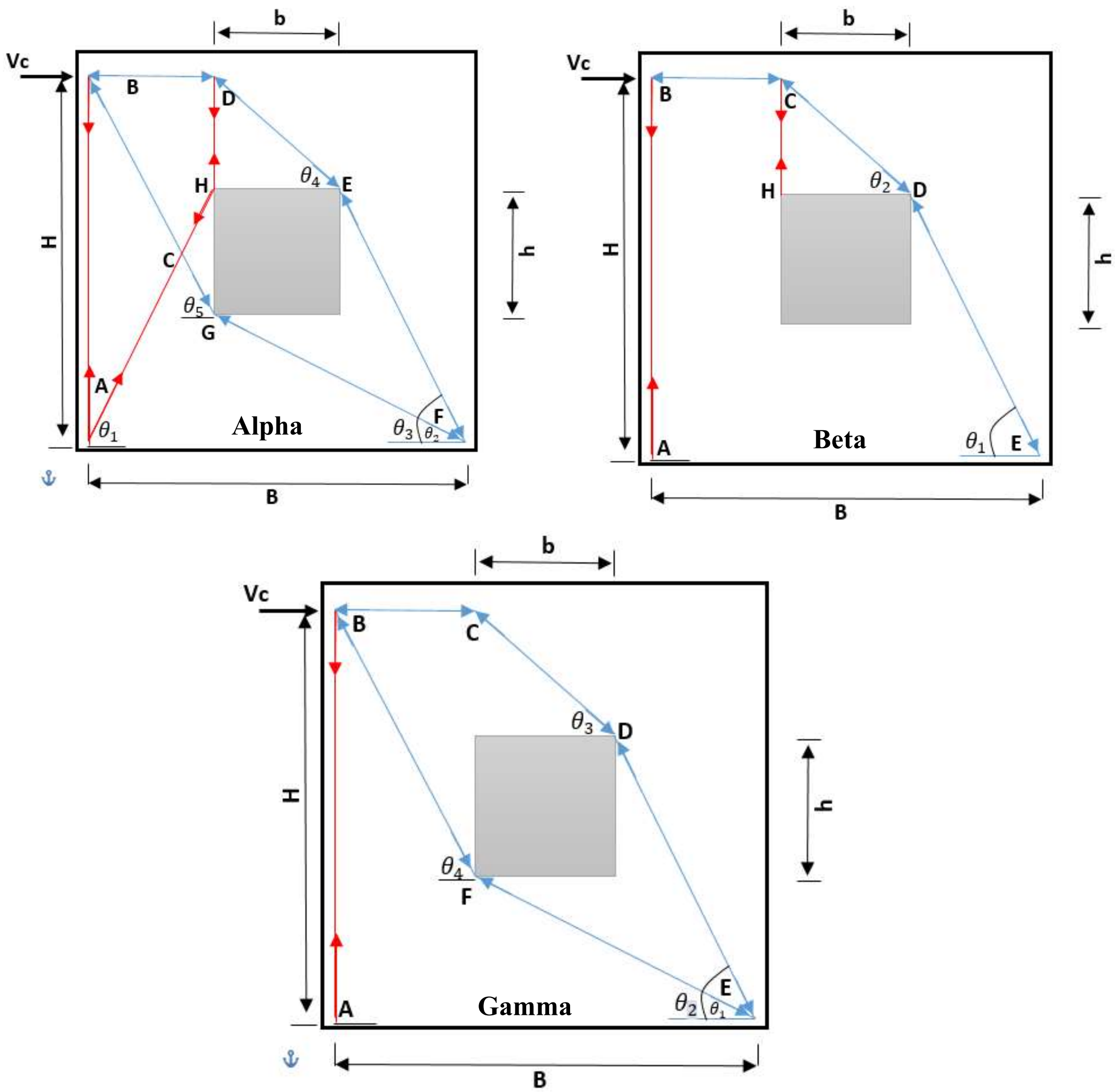


Figure 2. 7: Possible 3 Strut and Tie Models

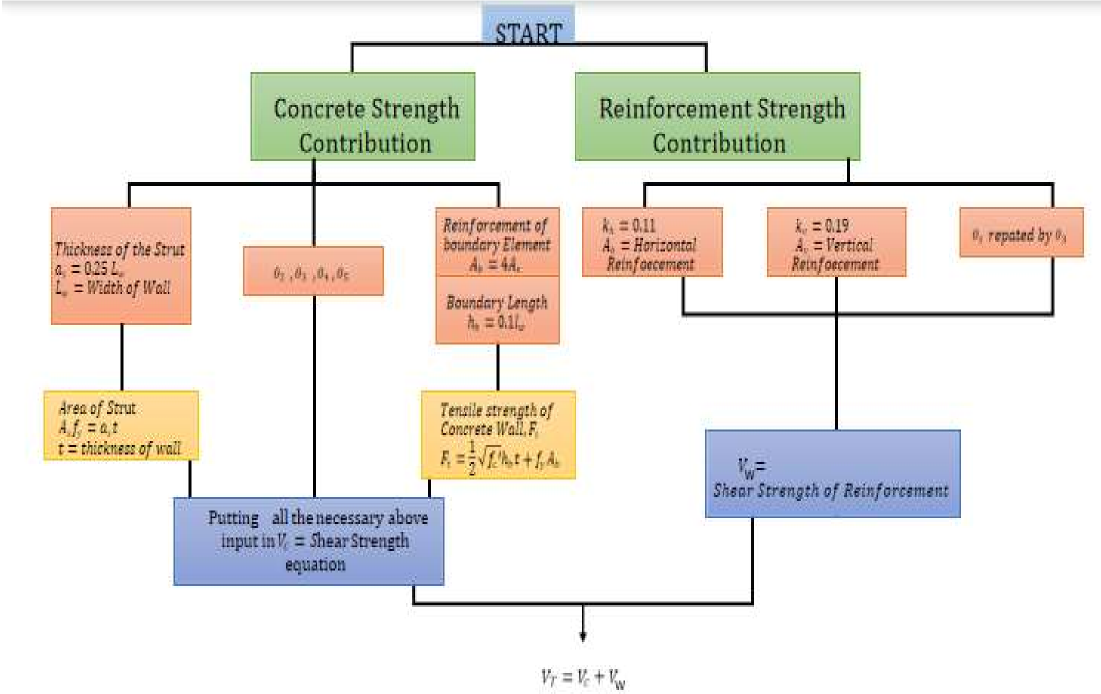


Figure 2. 8*:* Flow Chart for Trial and Error

From Table 2.1 it can be seen that alpha beta and gamma percent errors relevant to the FEM analyzed results are calculated and among that Gamma model percent error is least, so gamma model is taken as our proposed finalized model. Moreover the benefit of adopted strut and tie models trial and error procedure is that the best possible arrangements of struts and ties is taken for strength calculation which increases chances of accurate results prediction. Also gamma model as depicted in table 2.1 is most appropriate which can also be seen clearly from its struts arrangement which is most close to the Finite element analyzed stress contours.

Taking finalized Strut and Tie model i.e. Gamma model, (Figure 2.9) analysis and formulation is described under:

Table 2. 1 Trial and Error Results Comparison

TRIAL AND ERROR				
Model Type	Analytical Results (KN)	Numerical Results (KN)	Percent Error	Remarks
Alpha	115.98	155.4	-25.36%	In appropriate
Beta	102.65	155.4	-33.94%	In appropriate
Gamma	148.84	155.4	-4.221%	Appropriate

2.3 Proposed Strut and Tie model

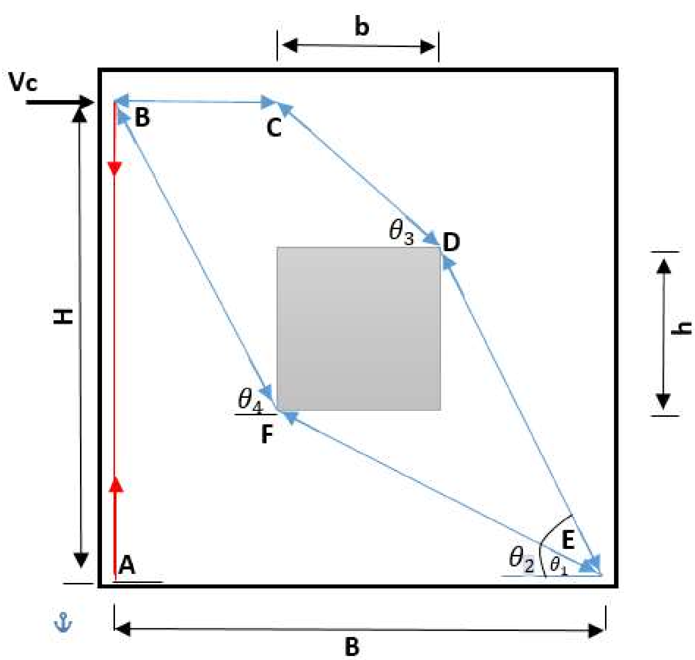


Figure 2. 9: Proposed Strut and Tie model

The proposed diagonal strut mechanism contains 6 nodes having strut-strut, strut-tie and tie-tie interaction at specific nodes depends upon the stress configuration due to proposed loadings. Each strut and tie is inclined with certain angle, value of each angle if alters will alter the results. So in the model proposed each angle is linked with opening dimensions like if an opening dimension or aspect ratio changes the inclination angle will change and in consequence the results will be changed for each specific change in opening dimensions, thus giving best single predicted model that can accommodate every change in wall parts including opening aspect ratio. Same linkage of force transfer mechanism with opening dimensions is utilized in truss model.

2.3.1 Shear strength formulations

To get a versatile shear strength equation As per the proposed STM model, concrete crushing at the bottom is assumed as a failure state so the flow of forces has been defined that are going from top of the wall to its bottom through various nodes.

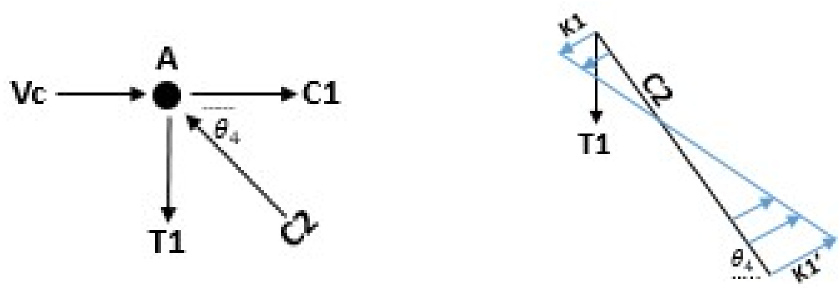


Figure 2. 10: Node A forces plus tensile stresses on strut due to a linked tie

Starting with first node near loading that is Node A (figure 2.10), equilibrium conditions were used to write each strut and tie force in terms of shear force and inclination angle;

$$T1 = 0.7Vc\ tan\,\theta_4$$

$$C1 = 0.3Vc$$

$$C2 = \frac{Vc-0.3Vc}{cos\,\theta_4} = \frac{0.7Vc}{cos\,\theta_4}$$

$$Where: \theta_4 = tan^{-1}\left(\frac{\frac{H}{2}+\frac{h}{2}}{\frac{B}{2}-\frac{b}{2}}\right)$$

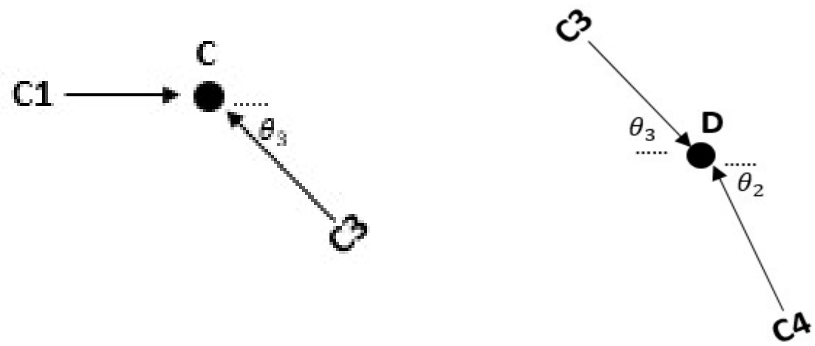


Figure 2. 11: Node C & D attached forces

Additionally the concept of transverse force developed along strut due to a tie linked with it is also added in the calculation because a tensile force of tie will tend to impose A non-uniform distribution of stress along the strut as illustrated in figure 2.10 which will reduce the strut capacity to endure compressive force, so incorporating this transverse force will make the calculations more real thus a non-uniform transverse distribution of stress is taken parallel to the strut that is linked to Node A[figure 2.10] . K1 and K1' being the Stress distribution factors associated with the bottom and top nodal zones. Ning et al,[30] found out their values through force and moment equilibrium at respective node and it turned out to be value of 4 for k1 and 2 for k1'. Before that Tan et al. [31] proposed k = 2 by assuming rectangular stress distribution as he only satisfied force equilibrium.

Similarly Node C and D equilibrium equations are written and respective linked strut and ties forces are written in form of its inclination and shear force.

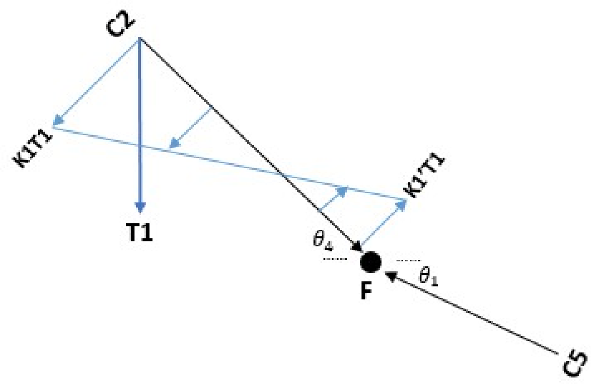


Figure 2. 12: Node F attached forces

$$C3 = \frac{0.3Vc}{cos\ \ _{3}}$$

$$Where:\ \theta_3 = tan^{-1}\left(\frac{\frac{H}{2}-\frac{h}{2}}{b}\right)$$

$$C4 = \frac{0.3Vc}{cos\,\theta_2}$$

$$\theta_2 = \tan^{-1}\left(\frac{\frac{H}{2}+\frac{h}{2}}{\frac{B}{2}-\frac{b}{2}}\right)$$

$$C5 = \frac{0.7Vc + 0.7k1Vc\sin\theta_4}{\cos\theta_1}$$

As all the forces approaching to the bottom are defined, Node E [figure 2.13] being the bottom node is taken to get the required shear strength equation, while doing the formulations another concept termed as softening effect of concrete which is defined as The reduction in the structure's load capacity of concrete under loadings due to the coalesce phenomena of micro cracks which forms a zone of weakness in concrete to take compression load [32]. So keeping this in mind we can't just apply equilibrium condition and find out an equation as it would give us wrong or less conserved strength that can lead to damage of structure prior to the required demand. Therefore softening effect of concrete is indulged in this research by using A failure criterion for nodal zones (under tension-compression stress states) based on Mohr–Columb theory is as follows:

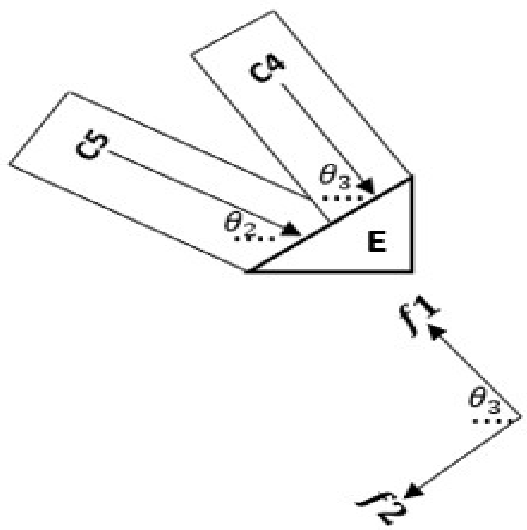


Figure 2. 13: Node E attached forces

$$\frac{f1}{fc} + \frac{f2}{ft} = 1$$

In this context, $f1$ and $f2$ represent the principal nature of tensile and compressive stresses at the nodal based zone, respectively; fc is the cylinder compressive strength, which denotes the high compressive based strength in the f2f_2f2 direction; and ft indicates the high tensile based strength. Ning et al. [30] also demonstrate that interactive failure criteria, such as Mohr's failure criterion, account for the softening effect and nature of concrete strength caused by transverse tensile strain. The softening effect in their model is comparable to the equations proposed by MCFT (Vecchio and Collins [33]) and Belarbi and Hsu [34]. The stresses f1, f2 plus the forces acting on node E [] is considered and equilibrium condition is applied to get the shear strength equation for concrete presented as;

Equilibrium condition for f1;

$f1 - C4 - C5\cos(\theta_3 - \theta_2) = 0$

Arranging equation (7) to get;

$f1 = C4 + C5\cos(\theta_3 - \theta_2)$

Similarly for f2 applying equilibrium condition to get;

$f2 - C5\sin(\theta_3 - \theta_2) = 0$

After arranging equation 9 we got;

$f2 = C5\sin(\theta_3 - \theta_2)$

Knowing C4 and C5 all other strut and ties formulas in terms of shear stress plus inclination is found out too as given;

C4 = $\frac{0.3Vc}{\cos\theta_2}$

$C5 = \frac{0.7Vc + 0.7k1Vc\sin\theta_4}{\cos\theta_1}$

Where the inclinations θ_1, θ_2 $and\ \ \theta_3\ are\ shown\ as\ under$;

$\theta_1 = \tan^{-1}\left(\frac{\frac{H}{2}+\frac{h}{2}}{\frac{B}{2}-\frac{b}{2}}\right)$, $\theta_2 = \tan^{-1}\left(\frac{\frac{H}{2}-\frac{h}{2}}{\frac{B}{2}+\frac{b}{2}}\right)$ and $\theta_3 = \tan^{-1}\left(\frac{\frac{H}{2}+\frac{h}{2}}{\frac{B}{2}-\frac{b}{2}}\right)$

Now putting equation "8" and "10" in equation "7" to get the concrete shear strength;

$$\frac{C4 + C5\cos(\theta_3 - \theta_2)}{fc.Astr} + \frac{C5\sin(\theta_3 - \theta_2)}{ft.At}$$

$$= 1$$

"Astr" being concrete strut area and As per Hwang et al. [35] and Kassem [36], the cross-sectional area of the concrete strut, Astr, can be expressed as follows::

$$Astr = tw * ac$$

"tw" represents the thickness dimension of wall web, and "ac" is the depth of strut of diagonal position, as suggested by Hwang et al. [35]. They took that the depth of the diagonally induced concrete strut is approximately equal to the depth of the flexural compression zone of elastic columns, ac[37]. Specifically, this is expressed as:

$$ac = \left(0.25 + 0.85\frac{N}{Awfc}\right)Lw$$

(16)

where Here, Aw denotes the total cross-sectional area of the wall, and N/AwFc represents the axial load ratio. Another term, ft.At, refers to the tensile strength of the concrete wall. This term is recommended by Panatchai et al. [38], as shown below:

$$ft.At = Abe.fybe + 0.5\sqrt{f'c}\ bb.hb$$

Here, Aberepresents the total cross-sectional area of the boundary longitudinal reinforcement, fyb is its yield strength, bb is the width of the boundary elements, and $0.5\sqrt{fc}$ denotes the splitting tensile strength of the concrete. [38]

Further resuming the shear strength formulations (equation "15"), putting strut and tie equations ("11","12" and "13") in terms of shear force and angles in equation "15" to get the following,

$$\frac{\frac{0.3Vc}{\cos\theta_2}+\frac{0.7Vc+0.7k1Vc\sin\theta_4}{\cos\theta_1}\cos(\theta_3-\theta_2)}{fc.Astr}+\frac{\frac{0.7Vc+0.7k1Vc\sin\theta_4}{\cos\theta_1}\sin(\theta_3-\theta_2)}{ft.At}=1$$

Taking Vc as common,

$$Vc\left[\frac{\frac{0.3Vc}{\cos\theta_2}+\frac{0.7Vc+0.7k1Vc\sin\theta_4}{\cos\theta_1}\cos(\theta_3-\theta_2)}{fc.Astr}+\frac{\frac{0.7Vc+0.7k1Vc\sin\theta_4}{\cos\theta_1}\sin(\theta_3-\theta_2)}{ft.At}\right]=1$$

Arranging the above equation by taking Vc on one side and the rest on another side of equal to get most versatile shear strength equation ("19") as shown below,

$$Vc=\frac{1}{\frac{\frac{0.3Vc}{\cos\theta_2}+\frac{0.7Vc+0.7k1Vc\sin\theta_4}{\cos\theta_1}\cos(\theta_3-\theta_2)}{fc.Astr}+\frac{\frac{0.7Vc+0.7k1Vc\sin\theta_4}{\cos\theta_1}\sin(\theta_3-\theta_2)}{ft.At}}$$

2.3.2 Shear strength formulations contributed by Truss mechanism

The truss model developed by Panatchai et al,[38] (figure 2b) is evaluated and utilized in this paper. It consists of horizontal and vertical trusses with its sub trusses that acts as struts and ties based on their force taking mechanism. After analysis and applying equilibrium condition, shear strength equation contributed by web reinforcement is expressed as below:

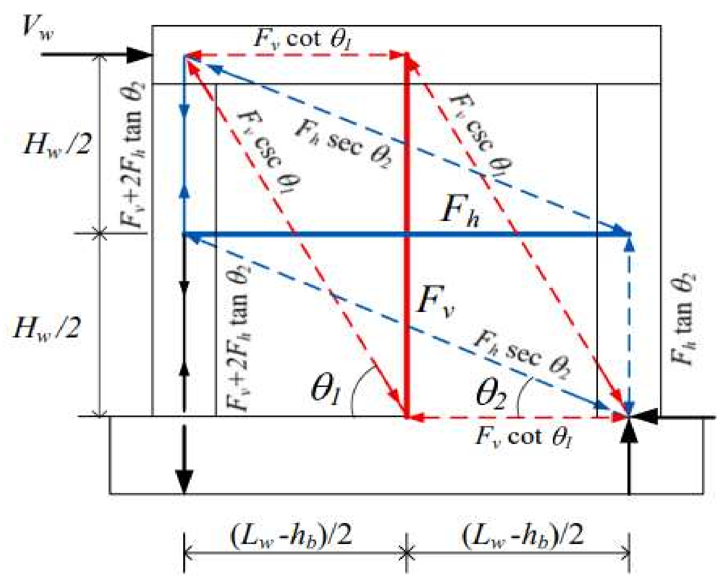


Figure 2. 14: Truss mechanism for reinforcement contribution

$Vw = Fh + Fv \cot \theta_s$

The above equation indicates that only lateral and vertical ties added up to the shear strength Vw Typically, during shear failure in squat shear walls, the lateral and vertical web reinforcements may not reach their yield strengths [18–20]. Consequently, the shear strength Vw can be expressed as follows:$Vw = k_h A_h F_{yh} + k_v A_v F_{yv} \cot \theta_3$

θ_s Is being replaced by θ_3 because the main strut [figure 1] that is connected to the node D for which we have assumed concrete crushing and is used for formulation of concrete shear strength is inclined with angle θ_3. k_h and k_v are two empirical constants whose values are optimized by Panatchai et al,[38] through the use of Fmincon function in matlab to minimize The coefficient of variation for the experimental-to-predicted strength ratios is found to be

0.11 for k_h and 0.19 for k_v. Ah and Av denote the total cross-sectional areas of the lateral and vertical steel bars in wall web, respectively, and fyh and fyv are their corresponding yield strengths, respectively.

The predicted STM based strength equation cannot predict the accurate shear strength for perforated squat wall, infact it gives an overestimate of shear strength contributed by web reinforcement because the reinforcement eliminated in the opening area is also used in above equation but on ground the empty space (opening) in squat wall isn't contributing anything to resist applied shear force. So another perimeters Ah' and Av' that gives horizontal and vertical reinforcement area being cut down in the opening area when making a reinforcement cage for squat wall. So a modified form of equation "21" is expressed below, that will cater the opening area deduction plus any change in opening area and aspect ratio.

$$Vw = k_h(A_h - A'_h)F_{yh} + k_v(A_v - A'_v)F_{yv} \cot \theta_3$$

(22)

Equation "18" and "22" when substituted in equation "1' "will give you the peak shear strength for squat walls having openings of different aspect ratio.

$$V = Vc + Vw$$

Substituting both Vc and Vw, we get;

$$V = 1\Bigg/\left[\left\{\left|\frac{0.7 + 0.7k1sin\theta_5}{cos\theta_2}\{\cos(\theta_3 - \theta_2)\} + \frac{0.3}{cos\theta_3}\right|\Bigg/(A_{str}f_c')\right\} + \left\{\left|\frac{0.7 + 0.7k1sin\theta_5}{cos\theta_2}\{\sin(\theta_3 - \theta_2)\}\right|\Bigg/(Asftn)\right\}\right]$$

$$+ k_h(A_h - A_{h'})f_y + k_v(A_v - A_{v'})f_y\ cot\theta_3$$

2.4 Opening size plus aspect ratio effects on strength through proposed Diagonal strut and truss mechanism

This section has been written to make sure if aspect ratio of opening plus area changes, the shear strength equation is catching the effects and in return gives accurate results. To evaluate the heading words, three different aspect ratio openings [figure 2.15] were taken, first one is square having aspect ratio 1:1, second one horizontal rectangle shape having 2:1 aspect ratio and third one being vertical shaped rectangle bearing 1:2 aspect ratio.

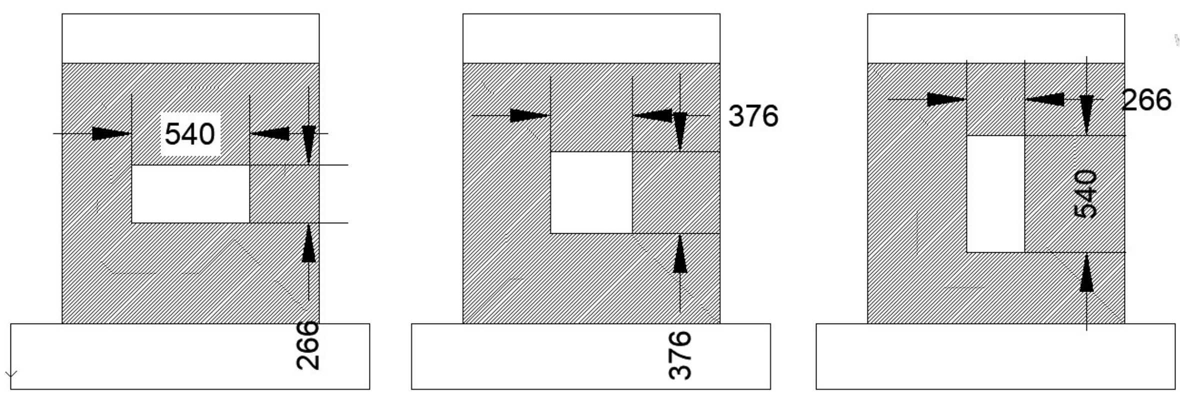


Figure 2. 15: Squat Walls with different aspect ratio openings

The concrete squat wall properties, dimensions plus reinforcement details were taken from Muhammad et al, [39] published work and opening area was taken as 10 percent of squat wall area as recommended by International building code (IBC) 2021[40] section [7-9]. As all the details necessary to be put in equations are known, inclination of struts and ties for each opening aspect ratio is found out through above equations Fc', Fy and reinforcement area being known from Muhammad et al, [39] paper. All the required inputs are placed in strength equation & for square opening squat wall is found out to be 148.84 KN. Same required inputs are found out for 2:1 and 1:2 aspect ratio opening in squat wall and corresponding shear strength are found out to be 137.34 KN and 158.73 KN respectively. Additionally, area of opening is changed for each aspect ratio in order to check if the formulated strength equations takes it. So area is being increased by 1.5 times for each aspect ratio opening (square, horizontal rectangle, vertical rectangle) squat wall and the results were found out to be 127.01 KN for square, 110.03 KN for 2:1 aspect ratio and 133.71 KN for 1:2 aspect ratio opening concrete walls. All the result making data including shear strength results are summarized in [table 3.1]. It is crystal cleared from the summarized data that the proposed model is considering any change in aspect ratio plus area of openings which proves its novelty. Further the results that are given by the proposed model needs to be validated in order to prove its accuracy. So validation of this model is discussed in below section.

Table 3. 1 Strength Prediction for each change in aspect ratio & area of openings

Proposed STM strength equation results		
Model (Aspect Ratio)	Opening Area (mm2)	Analytical Results (KN)
2:1	**540 x 266**	**137.34**
1:1	**376 x 376**	**148.84**
1:2	**266 x 540**	**158.73**
2:1	**810 x 399**	**110.02**

1:1	**564 x 564**	**127.01**
1:2	**399 x 810**	**133.71**

Chapter 3 : Validation of Proposed Model

The proposed model is validated by two approaches, first one is experimental and second one is numerical modeling. Both of them is explained in below portions.

3.1 Experimental Validation

The experimental setup contained a scaled (1:3) reinforced concrete squat wall having vertical shape (aspect ratio of 1:2) opening subjected to lateral monotonic quasi static loading in order to know its ultimate shear strength. Experimental model was taken from experimental work done by Muhammad et al, [39] which contained two beams (one loading beam and second foundation) and a web having width 1180 mm, height 1200 mm and thickness 100 mm [figure 3.1]. The reinforcement ratio of the wall web was taken as 1.03% in the transverse direction and 1.05% in the vertical direction, according to the work of Muhammad et al. [39]. The web featured a mesh with two layers of reinforcing bars, each with a diameter of 8 mm (0.31 in.), uniformly spaced at 100 mm (3.94 in.) center-to-center in both directions. [figure 3.1]. The loading beam and foundation beam dimensions plus reinforcement details were taken as per lab requirements shown in figure 3.1. The opening size was taken as 10 percent of the selected squat wall as per standard of International building code (IBC) 2021[40] section [7-9] which was found out to be 266 mm by 540 mm illustrated in figure 3.1 The concrete used for casting included a proper mix ratio of 1:1.5:3 having aggregate size 1” down, whose crushing strength defined as fc’ was found out by standard method of casting three cylinders [figure 3.3] as per section C39 of ASTM [41]. After 28 days of curing the same cylinders were tested under an axial load applied by Universal testing machine (UTM) and an average of all 3 samples compressive strength is taken and it is turned out to be 21mpa.

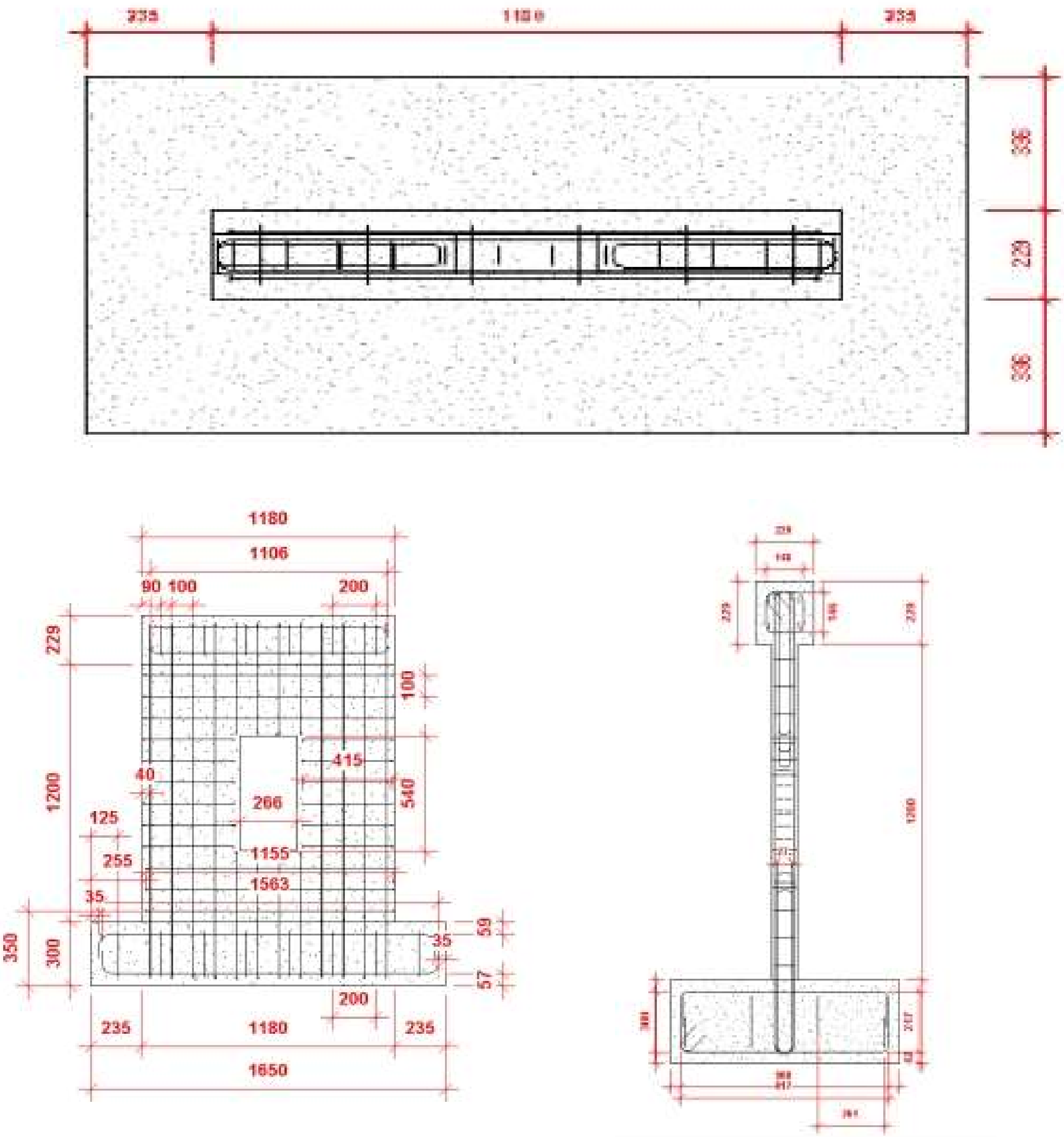


Figure 3. 1: Reinforcement Details of experimental model with elevation, plan and sectional view

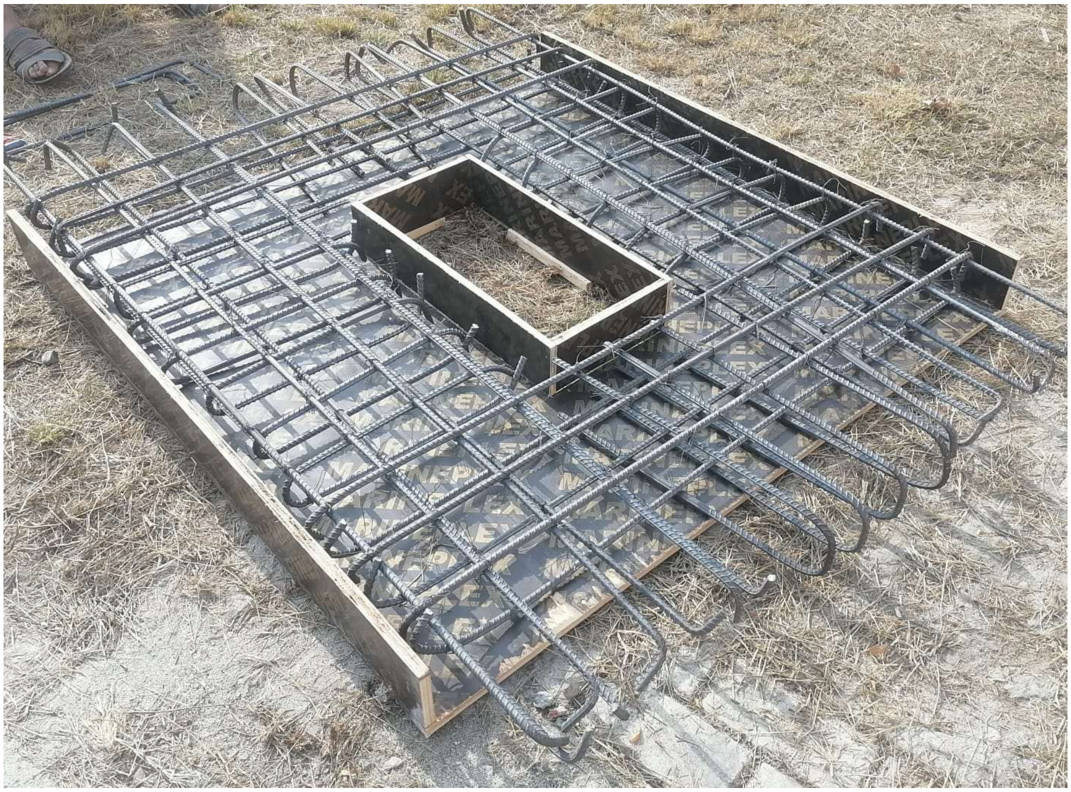


Figure 3. 2: Reinforcement of Wall web

Figure 3. 3: Cylindrical Concrete Specimens

Figure 3. 4: Casted Squat Wall

Figure 3. 5: Experimental Frame work for experimental model

Using defined mixed ratio and other required particulars, the concrete squat wall along with two beams are casted and cured for 7 days the casted wall along with formwork is shown below in Figure 3.5.

The casted wall after 28 days were put in the frame of testing including the arrangement of reaction frame, sticking the foundation of wall to the reaction floor with the help of 2" bolts and was subjected to the hydraulic jack having 100 Ton capacity. The whole experimental setup, loading platform and experimental perimeters of wall are described in figure 3.5

Figure 3. 6: Crack Pattern of tested wall

LVDT is installed at the top of the wall to know its top linear displacement, both LVDT and load cell IS attached to the data lodger to screen out the curve of load vs displacement. After all the arrangements for testing were fulfilled the wall was put in to quasi static lateral load through loading beam and continued till the fracture or when resisting load in data lodger started decreasing after attaining a peak and the corresponding tested wall having cracks as well load vs displacement curve is shown in figure 3.6 and 3.7. Cracks are noted and defined whether which one is result of compression and which one is the result of tension. Tension cracks are usually in cracking form and the compression is in crushing form.

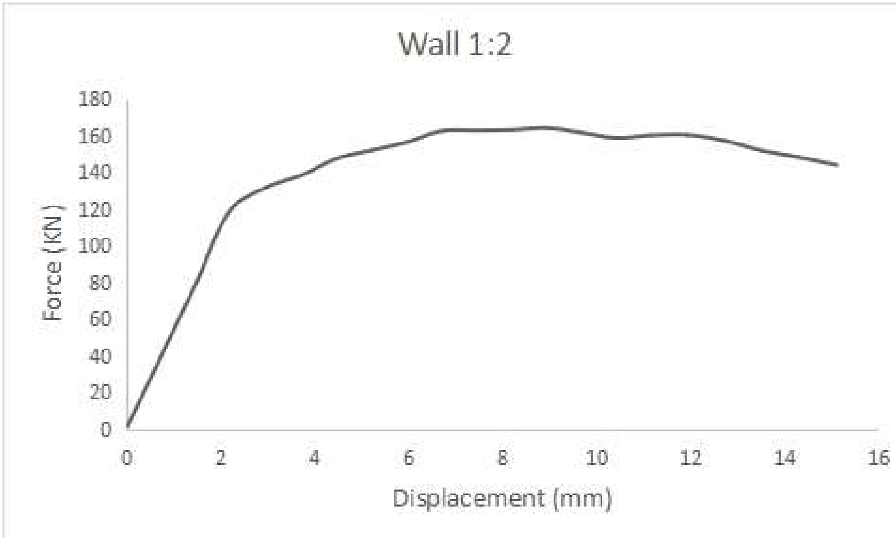


Figure 3. 7: Load vs Displacement Curve

The load versus displacement curve indicates that the peak shear load attained by the wall is 164.25 kN, with a top displacement of 8 mm. This result closely approximates the analytical predictions. A comparison of the results, including deviations, is presented in Table 3.2.

Table 3. 2 Experimental vs Analytical results

WALL TYPE	EXPERIMENTAL RESULTS		Analytical	% Error
	Top Displacement(mm)	Peak Load(KN)	Peak Load	
1:2(Aspect ratio)	8	164.25	158.73	-3.77%

3.2 Numerical Validation

The proposed model is numerically validated through two procedures, first through simulation of perforated squat wall having 540mm x 266mm opening size, where the said wall was modeled in finite element based software ABAQUS 2020 version, where beam, foundation and web was modeled separately using 3D parts space modeling and deformable type, all three parts were then merged together to form experimentally resembled wall as shown in figure 13. The foundation was made fixed to not permit any sort of displacement and rotation as illustrated below in boundary condition diagram. The concrete was modeled using 3-Dimension 8-noded brick element (C3D8R) whereas for reinforcement 3-Dimension 2-Noded wire element was employed. For determining optimum mesh size, sensitivity analysis was conducted and got best possible mesh size shown below in figure model mesh. The interface region between beam web and web foundation was made realistic by employing embedded constraint. Load was applied at the top laterally.

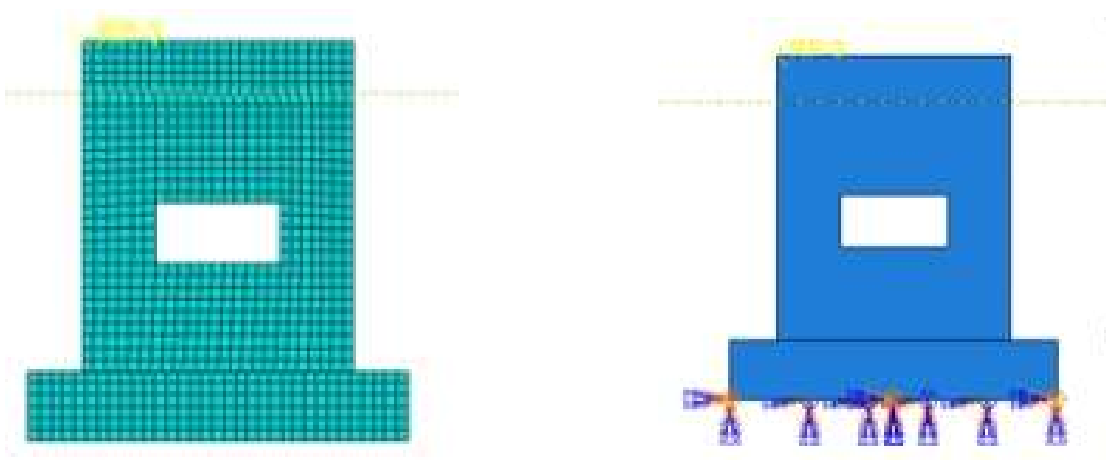


Figure 3. 8: Boundary and mesh details of FEM wall

For analysis of the modeled wall, concrete damaged plasticity (CDP) model was adopted for inheriting concrete behavior with key inputs illustrated in table 2 and 3 and for reinforcement modeling steel elastic-plastic constitutive model with strain hardening was employed with its properties shown in table 4.

Table 3. 3 Concrete material properties

Properties	Values
Compressive strength fc'	21 Mpa
Poisson ratio	0.19
Density	2.4 g/cm3

Table 3. 4: Steel Material Properties

Properties	Values
Yield Tensile strength, fy	276 Mpa
Poisson ratio	0
Density	8.05 g/cm3

Table 3. 5: Analysis parameters

Parameters	Values
Dilation angle (degrees)	40
Eccentricity	0.1
Bi-axial strength relative to uniaxial strength	1.16
Second invariant stress ratio	0.667
Viscosity parameter	0

After the analysis has been run, the forces are transferred from top to the bottom making stress and displacement contours as shown in following figures, reaction force at the bottom is obtained by summing all the reaction forces at bottom nodes and displacement is attained at the top.

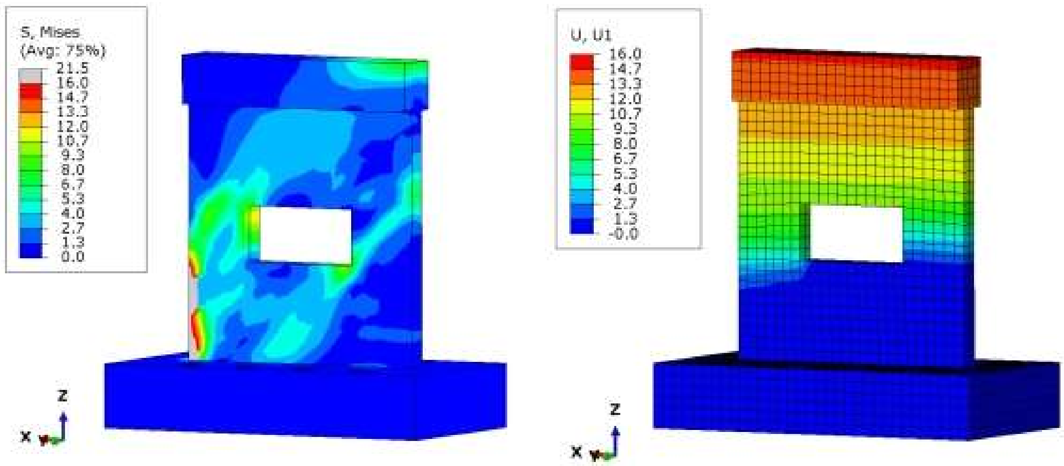


Figure 3. 9: Von Mises Stress Contour and Displacement U1

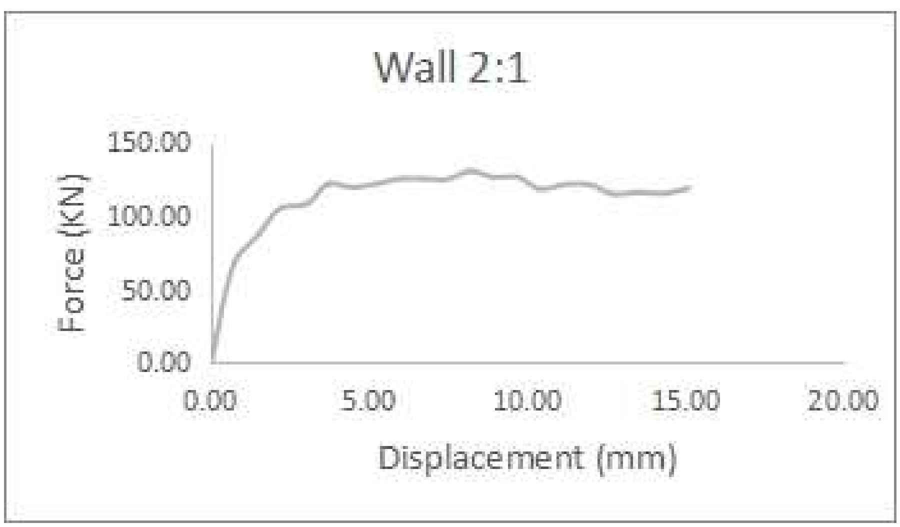


Figure 3. 10*:* Load Vs Displacement Curve

A load vs displacement curve was obtained after complete analysis, where the wall behavior was completely linear till small displacement of around 0.95mm displacement corresponding to 72KN shear load, after that cracks starts developed and the wall attained a peak load of 130.6KN at 8.2mm as shown below in load vs displacement curve.

The results such as peak shear load obtained from FEM analysis shows very small variation from analytical peak shear load obtained from our proposed equation "1" and the summary is shown below in table 8.

Table 3. 6: Numerical vs Analytical results

WALL TYPE	Numerical Results		Analytical	% Error
	Top Displacement(mm)	Peak Load(KN)	Peak Load	
2:1(Aspect ratio)	8	130.6	137.34	+5.34%

Chapter 4 : Conclusion

This paper presents a modified softened strut and tie modeling approach proposed by the author for reinforced squat wall having different aspect ratio openings. The model introduced is capable of catching any changes in aspect ratio plus area of openings in squat wall with proven accuracy which is enlighten through the validation mainly by experimental results of squat wall having 2:1 aspect ratio opening and also numerical approach of FEM analysis of squat wall having 1:2 opening in abaqus software is utilized for confirmation of proposed model outcomes. The comparison of proposed model The results were in close alignment with both experimental and numerical results with accuracy of 93.13% and 93.89%. It is therefore recommended to follow the proposed formula on fields in order to accurately predict the change in shear strength if certain aspect ratio opening needs to be introduced in reinforced squat walls. Also following points are well concluded from this research which are;

- The model introduced is very much forcasting the accurate results for each change in aspect ratio of wall openings
- The model introduced can also Forecast the shear strength of increase or decrease in opening size for a squat wall
- Proposed workings reduced the working load of structural analyst and designers

Chapter 5 : References

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