Bukti Korespondensi Artikel:
“Simplified Strut-and-Tie Model for Shear Strength Prediction of Reinforced Concrete Low-Rise Walls”

Terdiri dari:

1. Submission pertama (9 November 2020)
2. Revisi pertama: Major Revisions Requested (18 Februari 2021)
3. Submission kedua (3 Juli 2021)
4. Paper diterima (12 Oktober 2021)
5. Submission final (21 Oktober 2021)
6. Pengecekan author galley sebelum terbit dan koreksinya (10-14 Februari 2022)

1. **Submission pertama (9 November 2020)**

ACI Structural and Materials Journals

Preview (S-2020-477.R1)

From: Journals.Manuscripts@concrete.org
To: chandra.jimmy@petra.ac.id
CC:
Subject: Manuscript ID S-2020-477 - Manuscript Receipt Acknowledgment
Body: 09-Nov-2020

Dear Dr Jimmy Chandra

Thank you for submitting the manuscript titled, "Simplified Strut and Tie Model for Shear Strength Prediction of Reinforced Concrete Low Rise Walls," for possible publication in the ACI Journals. Please refer to Manuscript ID S-2020-477 in all correspondence regarding this manuscript.

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Date Sent: 09-Nov-2020

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To: chandra.jimmy@petra.ac.id

Mon, Nov 9, 2020 at 7:40 PM

09-Nov-2020

Dear Dr Jimmy Chandra

Thank you for submitting the manuscript titled, "Simplified Strut and Tie Model for Shear Strength Prediction of Reinforced Concrete Low Rise Walls," for possible publication in the ACI Journals. Please refer to Manuscript ID S-2020-477 in all correspondence regarding this manuscript.

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Sincerely,
Ms Angela Matthews
Journals.Manuscripts@concrete.org

2. Revisi pertama: Major Revisions Requested (18 Februari 2021)

Preview (S-2020-477.R1)

From: Journals.manuscripts@concrete.org
To: chandra.jimmy@petra.ac.id
CC:
Subject: Decision on Manuscript ID S-2020-477 - Major Revisions Requested
Body: 18-Feb-2021

Dear Dr Jimmy Chandra:

Reviewers have recommended major revisions to the Manuscript S-2020-477 titled "Simplified Strut and Tie Model for Shear Strength Prediction of Reinforced Concrete Low Rise Walls." The manuscript, in its present form, is not accepted and will require revisions, resubmission, and rereview.

The reviewers provided comments and suggestions that can assist in improving the manuscript. The comments are included at the end of this email. Please know not every reviewer provides comments. When addressing the comments, you must prepare an item-by-item summary of your responses to each reviewer in a separate file which must accompany the subsequent resubmission.

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Thank you for your contribution to the ACI Journals. We look forward to receiving the revised manuscript.

Sincerely,
Ms Angela Matthews
Journals.manuscripts@concrete.org

Reviewer(s)' Comments to Author:

Reviewer: 1

Comments and Suggestions for the Author(s)
This manuscript proposes an analytical model based on strut and tie concept to predict the shear strengths reinforced concrete (RC) low rise wall. A total of 100 RC low rise wall specimens are used to verify the reliability of the proposed model. This study is valuable to predict the shear strengths of RC low rise wall and can help to revise the current concrete codes. There have some problems should be explained before this paper can be published.
(1) In Equation (2), the expression is P+T=R. However, the directions of these three forces are same, as shown in Figure 2. Is it right? The author should explain that.
(2) In the proposed modified model, the definition of the depth of compression zone (c) is an important factor. Thus, in this model, the value of c is calculated using a formula that was derived using nonlinear finite element analysis. The author has not verified the validation of the adopted finite element model. Therefore, it is advised to verify the FEM.
(3) In the line 16 of page 8, the axial load ratio (ARL) used in this paper include 0, 0.1 and 0.2. However, it is impossible for the case of axial load ratio of 0. So, the author could select more reasonable axial load ratio. (For example 0.1, 0.2, 0.3 or etc.)
(4) In Line 23 of page 8, is it P/fc’ or P/fc’Aw.
(5) In the comparisons, the authors have selected Vexp/Vn. Maybe the authors can consider Vn /Vexp. Because, in general, the test value is considered as the actual value and is used as a benchmark.
(6) For the evaluation of proposed model, the author should state more detailed. The average of the proposed model is not best (1.35 is slightly larger than 1.29 of Hwang-Lee model). However, the proposed model has smallest standard derivation and coefficient of variation. Thus, the author can state that the proposed model is best by comprehensively consideration.

Reviewer: 2

Comments and Suggestions for the Author(s)
If the manuscript is agreed to be published in ACI journal, the following are suggested for further improvement.
1. As the effect of the confinement of concrete due to both longitudinal and transverse stirrups in the wall is

included in the expression of the capacity of diagonal compression strut, the reviewer thinks it seems that it belongs to generalized strut and tie model. Hence, it's better to mention it in words, although it is not shown in Fig.2 directly.
2. As many codes of nonlinear finite element analysis are available now, it is necessary to present an expression why ATENA is chosen and a simple description of the basic model.

Reviewer: 3

Comments and Suggestions for the Author(s)
See attached Review Comments.pdf

Reviewer: 4

Comments and Suggestions for the Author(s)
See attached S-2020-477_Proof_hi_Reviewed.pdf

Date Sent: 18-Feb-2021

File 1: - Review Comments.pdf

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Jimmy Chandra <chandra.jimmy@petra.ac.id>

Decision on Manuscript ID S-2020-477 - Major Revisions Requested

4 messages

ACI Structural and Materials Journals <onbehalfof@manuscriptcentral.com> Thu, Feb 18, 2021 at 11:10 PM
Reply-To: Journals.manuscripts@concrete.org
To: chandra.jimmy@petra.ac.id

18-Feb-2021

Dear Dr Jimmy Chandra:

Reviewers have recommended major revisions to the Manuscript S-2020-477 titled "Simplified Strut and Tie Model for Shear Strength Prediction of Reinforced Concrete Low Rise Walls." The manuscript, in its present form, is not accepted and will require revisions, resubmission, and rereview.

The reviewers provided comments and suggestions that can assist in improving the manuscript. The comments are included at the end of this email. Please know not every reviewer provides comments. When addressing the comments, you must prepare an item-by-item summary of your responses to each reviewer in a separate file which must accompany the subsequent resubmission.

To submit your revised manuscript, please enter your Author Center at https://mc.manuscriptcentral.com/aci.
- Your manuscript can be found in the "Manuscripts with Decisions" folder under "My Manuscripts."
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Thank you for your contribution to the ACI Journals. We look forward to receiving the revised manuscript.

Sincerely,
Ms Angela Matthews
Journals.manuscripts@concrete.org

Reviewer(s)' Comments to Author:

Reviewer: 1

Comments and Suggestions for the Author(s)
This manuscript proposes an analytical model based on strut and tie concept to predict the shear strengths reinforced concrete (RC) low rise wall. A total of 100 RC low rise wall specimens are used to verify the reliability of the proposed model. This study is valuable to predict the shear strengths of RC low rise wall and can help to revise the current concrete codes. There have some problems should be explained before this paper can be published.
(1) In Equation (2), the expression is P+T=R. However, the directions of these three forces are same, as shown in Figure 2. Is it right? The author should explain that.
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(3) In the line 16 of page 8, the axial load ratio (ARL) used in this paper include 0, 0.1 and 0.2. However, it is impossible for the case of axial load ratio of 0. So, the author could select more reasonable axial load ratio. (For example 0.1, 0.2, 0.3 or etc.)
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Reviewer: 2

Comments and Suggestions for the Author(s)
If the manuscript is agreed to be published in ACI journal, the following are suggested for further improvement.
1. As the effect of the confinement of concrete due to both longitudinal and transverse stirrups in the wall is included in the expression of the capacity of diagonal compression strut, the reviewer thinks it seems that it belongs to generalized strut and tie

model. Hence, it's better to mention it in words, although it is not shown in Fig.2 directly.
2. As many codes of nonlinear finite element analysis are available now, it is necessary to present an expression why ATENA is chosen and a simple description of the basic model.

Reviewer: 3

Comments and Suggestions for the Author(s)
See attached Review Comments.pdf

Reviewer: 4

Comments and Suggestions for the Author(s)
See attached S-2020-477_Proof_hi_Reviewed.pdf

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2 attachments

Review Comments.pdf
348K

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1138K

Jimmy Chandra <chandra.jimmy@petra.ac.id> Fri, Feb 19, 2021 at 1:41 PM
To: ACI Journal Review <Journals.manuscripts@concrete.org>

Dear Ms Angela Matthews,

Thank you very much for the review and comments for our paper. We will prepare the revisions as necessary. Furthermore, we would like to know when is the deadline to submit the revised paper?

I look forward to hearing from you.

Thanks and regards,

Jimmy
[Quoted text hidden]

ACI Journal Review <Journals.Manuscripts@concrete.org> Sat, Feb 20, 2021 at 1:48 AM
To: Jimmy Chandra <chandra.jimmy@petra.ac.id>

Dear Dr Jimmy Chandra,

Thank you for your email. Generally authors submit their revisions within 2 months, although we are willing to grant extensions when necessary. Feel free to contact me if you have any further questions.

Best regards,

[Quoted text hidden]

Jimmy Chandra <chandra.jimmy@petra.ac.id> Sat, Feb 20, 2021 at 7:10 AM
To: ACI Journal Review <Journals.Manuscripts@concrete.org>

Dear Ms Angela Matthews,

Thank you for your information. We will try to submit the revised paper within 2 or 3 months.

Thanks and regards,

Jimmy
[Quoted text hidden]

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3. Submission kedua (3 Juli 2021)

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Manuscript ID S-2020-477.R1 - Manuscript Receipt Acknowledgment

ACI Structural and Materials Journals <onbehalfof@manuscriptcentral.com> Sat, Jul 3, 2021 at 8:20 PM
Reply-To: Journals.Manuscripts@concrete.org
To: chandra.jimmy@petra.ac.id

03-Jul-2021

Dear Dr Jimmy Chandra

Thank you for submitting the manuscript titled, "Simplified Strut and Tie Model for Shear Strength Prediction of Reinforced Concrete Low Rise Walls," for possible publication in the ACI Journals. Please refer to Manuscript ID S-2020-477.R1 in all correspondence regarding this manuscript.

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Authors' Response to Reviewer Comments:

The authors would like to thank the reviewer for his or her careful review of the paper. Listed below are our responses to the comments.

Comments from Reviewer 1:

Comments and Suggestions for the Author(s)

This manuscript proposes an analytical model based on strut and tie concept to predict the shear strengths reinforced concrete (RC) low rise wall. A total of 100 RC low rise wall specimens are used to verify the reliability of the proposed model. This study is valuable to predict the shear strengths of RC low rise wall and can help to revise the current concrete codes. There have some problems should be explained before this paper can be published.

Comment #1:

In Equation (2), the expression is P+T=R. However, the directions of these three forces are same, as shown in Figure 2. Is it right? The author should explain that.

Response #1:

The authors apologize for creating confusion with the equation. The authors think that it may be better to explain in words (see page 7, line 14-16) for the combination of external axial load (P) and tension force (T) to become a resultant force (R). Thus, the equation is eliminated in the revised paper.

Comment #2:

In the proposed modified model, the definition of the depth of compression zone (c) is an important factor. Thus, in this model, the value of c is calculated using a formula that was derived using nonlinear finite element analysis. The author has not verified the validation of the adopted finite element model. Therefore, it is advised to verify the FEM.

Response #2:

Actually, the authors had verified the finite element model before using it to derive a formula to calculate depth of compression zone at the bottom of wall (*c*). However, the validation results were not presented in the previous version of the paper. In this revised paper, the validation of the finite element model has been added (see page 8, line 25 and page 9, line 1-5; Figure 3).

Comment #3:

In the line 16 of page 8, the axial load ratio (ARL) used in this paper include 0, 0.1 and 0.2. However, it is impossible for the case of axial load ratio of 0. So, the author could select more reasonable axial load ratio. (For example 0.1, 0.2, 0.3 or etc.)

Response #3:

The reason of choosing the axial load ratio ranging from 0.00 to 0.20 was that the data collected from literature (see Table 1) showed that most RC low rise walls were tested in this range. Indeed, many specimens were tested with zero axial loading. Of course, in real practice, it is impossible to have axial load ratio of 0.00. However, it may be possible for RC low rise walls to have very low axial load ratio (below 0.05). Furthermore, there is very rare case of RC low rise walls having axial load ratio more than 0.20. Therefore, to cover most cases, it is necessary to perform analysis with axial load ratio ranging from 0.00 to 0.20.

Comment #4:

In Line 23 of page 8, is it P/fc' or P/fc'Aw.

Response #4:

The authors have revised the sentence "The parameters f'_c and P are combined into one and normalized with wall web area to become $P/[f'_cA_w]$…" in this revised paper (see page 9, line 20-21).

Comment #5:

In the comparisons, the authors have selected Vexp/Vn. Maybe the authors can consider Vn /Vexp. Because, in general, the test value is considered as the actual value and is used as a benchmark.

Response #5:

The authors still prefer to display V_{exp}/V_n for comparison purposes. This is because it is more convenient to observe the conservatism of a method with value of V_{exp}/V_n above 1.00. Moreover, other strut and tie models [15, 16] also used V_{exp}/V_n when comparing with experimental results.

Comment #6:

For the evaluation of proposed model, the author should state more detailed. The average of the proposed model is not best (1.35 is slightly larger than 1.29 of Hwang-Lee model). However, the proposed model has smallest standard derivation and coefficient of variation. Thus, the author can state that the proposed model is best by comprehensively consideration.

Response #6:

The explanation has been added in conclusions (see page 13, line 17-24 and page 14, line 1-6).

Authors' Response to Reviewer Comments:

The authors would like to thank the reviewer for his or her careful review of the paper. Listed below are our responses to the comments.

Comments from Reviewer 2:

Comments and Suggestions for the Author(s)

If the manuscript is agreed to be published in ACI journal, the following are suggested for further improvement.

Comment #1:

As the effect of the confinement of concrete due to both longitudinal and transverse stirrups in the wall is included in the expression of the capacity of diagonal compression strut, the reviewer thinks it seems that it belongs to generalized strut and tie model. Hence, it's better to mention it in words, although it is not shown in Fig.2 directly.

Response #1:

The explanation of web reinforcement contribution as confinement to the diagonal compression strut has been added to the revised paper (see page 7, line 7-8).

Comment #2:

As many codes of nonlinear finite element analysis are available now, it is necessary to present an expression why ATENA is chosen and a simple description of the basic model.

Response #2:

The authors have added explanation about choosing ATENA software [17] (see page 8, line 23-25) as well as validation of the finite element model (see page 8, line 25 and page 9 line 1-

5; Figure 3) and description of the finite element model used in parametric study (see page 9, line 6-16; Figure 4).

Authors' Response to Reviewer Comments:

The authors would like to thank the reviewer for his or her careful review of the paper. Listed below are our responses to the comments.

Comments from Reviewer 3:

Comments and Suggestions for the Author(s)

This manuscript focused on the development of an analytical model based on strut and tie concept to predict the shear strength of a low-rise RC wall. This analytical model was developed with the assistance of nonlinear finite element analysis using ATENA software. The results of analytical model were compared with experimental results of 100 specimens from available literature to verify the accuracy of the proposed model.

Comment #1:

A summary of the results is in the table below:

$\frac{V_{exp}}{V_n}$	Number of specimens	Noted
(0.8 – 0.99)	7	Overestimates
(1.00 – 1.09)	11	Underestimates
(1.10 – 1.24)	16	Underestimates, conservative
(1.25 – 1.49)	34	Underestimates, low estimates, Not economical
≥ 1.5	32	Underestimates, Estimates are very Low, Not economical
Sum of Specimens	100	

Thus, it may not be practical to use this analytical model by structural engineers to estimate the shear strength of RC walls because 66% of the results are very underestimated, very conservative and are not economical. Therefore, I believe that the authors should find a solution to this problem so that the results of proposed model are closer to the experimental results.

Response #1:

The authors agree that the proposed strut and tie model is conservative. Indeed, when developing the model, the authors aimed that the model should be conservative enough in predicting the shear strength of RC low rise walls. The reasons for this are:

- Strut and tie concept is generally known as lower bound theory [14]. Thus, when it is done properly, it should give conservative results.
- Building codes always aim at safe predictions of the real strength of RC structures. For example, ACI 318 committee (in an article "Development of the One-Way Shear Design Provisions of ACI 318-19 for Reinforced Concrete", published in ACI Structural Journal, V. 116, No. 4, July 2019). In the article, the basis for revising current code provisions is explained and one of the key factors considered is safety. The committee aimed at V_{exp}/V_n above 1.00 if the strength reduction factor for shear (ϕ = 0.75) was applied, although this resulted in very conservative predictions (V_{exp}/V_n above 2.00) for some cases. The same philosophy was adopted by the authors when developing the proposed strut and tie model.
- As compared to building codes [4, 5] and other strut and tie models [15, 16], the proposed model is about similarly conservative, except for Eurocode 8 [5] that is extremely conservative. However, the proposed model has the lowest coefficient of variation (COV) of 0.19 as compared to other methods. Furthermore, the predictions of the proposed model are quite consistent and less scattered for wide ranges of wall height to length ratios and concrete compressive strengths.

Comment #2:

There are other studies using the Strut and Tie method to estimate the shear strength of RC walls that the authors have not considered in this manuscript:

1. Mun, J.-H., & Yang, K.-H. (2015). Strut-and-Tie Model for Shear Strength of Reinforced Concrete Squat Shear Walls. Journal of the Korea Concrete Institute, 27(6), 615–623.

2. Kassem, W. (2015). Shear strength of squat walls: A strut-and-tie model and closed-form design formula. Engineering Structures, 84, 430–438.

Response #2:

As suggested, the authors have added Kassem's strut and tie model [16] for comparison purposes. The analysis results can be seen in Table 1, Figures 9 and 10.

Comment #3:

Below is a collection of papers that the authors can use to enhance the comparison between results of proposed model and experimental results:

1. Oesterle, R.G., A.E. Fiorato, L.S. Johal, J.E. Carpenter, H.G. Russell, and W.G. Corley. 1976. Earthquake resistant structural walls-tests of isolated walls. Report to National Science Foundation.

2. Oesterle, R.G., J.D. Aristizabal-Ochoa, A.E. Fiorato, H.G. Russell, and W.G. Corley. 1979. Earthquake resistant structural walls-tests of isolated walls-Phase II. Report to National Science Foundation.

3. Chen, X.L., Fu, J.P., Hao, X., Yang, H. and Zhang, D.Y., 2019. Seismic behavior of reinforced concrete squat walls with high strength reinforcements: An experimental study. Structural Concrete, 20(3), pp.911-931.

4. Hidalgo, P.A., Ledezma, C.A. and Jordan, R.M., 2002. Seismic behavior of squat reinforced concrete shear walls. Earthquake Spectra, 18(2), pp.287-308.

5. Lefas, I.D., M.D. Kotsovos, and N.N.Ambraseys. 1990. Strength and deformation characteristics of reinforced concrete walls under load reversals. ACI structural journal, 87(6), pp.716-726.

6. Li, B., Pan, Z. and Xiang, W., 2015. Experimental evaluation of seismic performance of squat RC structural walls with limited ductility reinforcing details. Journal of Earthquake Engineering, 19(2), pp.313-331.

7. Salonikios, T., A. Kappos, A. Tegos, G. Penelis. 1999. Cyclic load behavior of low slenderness reinforced concrete walls: design basis and test results. ACI Structural Journal; 96(4):649–60.

Response #3:

The authors have considered these papers to be included for comparison purposes. The papers by Oesterle et al. (1976) and Oesterle et al. (1979) contain RC walls data that are similar to the ones that were published by Corley et al. [27]. The data had already been included in the paper for comparison purposes. Furthermore, RC walls tested by Hidalgo et al. (2002) were tested in double curvature manner. Since, the proposed strut and tie model was developed for cantilever RC walls, thus the data by Hidalgo et al. (2002) are not in included in the paper. This is because double curvature RC walls have different load path mechanism as compared to cantilever RC walls and hence it is not correct to use the load path mechanism that was developed in the proposed strut and tie model to predict the shear strength of double curvature RC walls.

The authors have also observed the papers by Lefas et al. (1990), Li et al. (2015), and Salonikios et al. (1999). However, the specimens tested in these papers failed in flexure mode, not in shear. Since the proposed strut and tie model was developed for predicting the shear strength of RC low rise walls, thus it is not correct to compare the RC wall shear strengths calculated from the model with the RC wall flexure strengths obtained from the experiment.

Authors' Response to Reviewer Comments:

The authors would like to thank the reviewer for his or her careful review of the paper. Listed below are our responses to the comments.

Comments from Reviewer 4:

Comments and Suggestions for the Author(s)

The comments were put directly into the paper draft. Thus, the authors think that it maybe better to reply the comments directly in the paper draft as attached below.

Simplified Strut and Tie Model for Shear Strength Prediction of Reinforced Concrete Low Rise Walls

Journal:	*ACI Structural and Materials Journals*
Manuscript ID	S-2020-477
Journal Name:	ACI Structural Journal
Date Submitted by the Author:	09-Nov-2020
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Keywords:	strut and tie, RC wall shear strengths, building code predictions

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SIMPLIFIED STRUT AND TIE MODEL FOR SHEAR STRENGTH PREDICTION OF REINFORCED CONCRETE LOW RISE WALLS

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Biography:

Jimmy Chandra is an Assistant Professor and currently Head of Structural Engineering Laboratory at Petra Christian University, Indonesia. He received his Doctor of Philosophy degree from Nanyang Technological University, Singapore. His research interests include behavior and seismic performance evaluation of reinforced concrete structures.

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ABSTRACT

In this study, an analytical model utilizing strut and tie concept was developed to predict reinforced concrete (RC) low rise wall shear strengths. In the model, failure mode considered was crushing of diagonal compression strut. In order to accurately determine the strut area, a formula for calculating depth of compression zone at the bottom of wall was derived with the aid of nonlinear finite element analysis. A total of 100 RC low rise wall specimens failing in shear obtained from available literature were used to verify the accuracy of wall strength predictions of the proposed strut and tie model. Furthermore, strength predictions from building codes and another analytical model were also included for comparison purposes. The analysis results show that the predictions of the proposed strut and tie model are quite conservative and they are more accurate than other methods' predictions. In addition, the predictions of the proposed model are quite consistent and less scattered for wide ranges of wall height to length ratios and concrete compressive strengths.

Keywords: strut and tie; RC wall shear strengths; building code predictions.

INTRODUCTION

The use of reinforced concrete (RC) walls ~~becomes~~ increasingly popular nowadays due to their superior performance against lateral ~~loadings~~ such as wind and earthquake loadings [1]. In addition, not only for lateral loadings, RC walls can also be utilized to resist gravity loadings as well. Thus, it is important to be able to determine the strength of RC walls accurately in order to provide safe and economical design, as these are two major concerns for structural engineers. Previous studies by the authors [2, 3] show that flexure strength of RC walls can be reasonably well predicted using flexural theory for member subjected to axial load and bending moment. However, for the shear strength, empirical building code formulas [4, 5] underestimate RC wall shear strengths by significant margin, especially for high strength concrete (HSC) walls and the overall predictions are quite scattered. Therefore, there was a need to develop an analytical model based on rational theory to accurately predict the shear strength of RC walls.

The rational theory for predicting RC members shear strength was developed in early 1900s based on the truss analogy [6, 7]. The theory was further developed in order to predict the shear strength of RC members more accurately [8, 9]. For RC low rise walls, many research have been conducted in order to predict the shear strength [10-13]. All those theories are able to predict the shear strength of RC low rise walls with certain accuracy. However, in their truss models, it was assumed that shear stress distribution over entire wall cross section was uniform which only valid for certain cases of RC low rise walls. Moreover, the calculation of RC low rise wall shear strengths using their models needs an iterative procedure to obtain solution that satisfies equilibrium and compatibility conditions as well as constitutive law of materials. Thus, it may not be practical to be used by engineers to estimate the shear strength of RC low rise walls.

In this study, an analytical model for predicting RC low rise wall shear strengths was developed based on strut and tie concept. RC low rise walls having height to length ratio (H_w/L_w) less than 2.5 can be categorized as disturbed regions where plane section does not remain plane. In this case, strut and tie model is considered as a rational approach to predict the strength of disturbed regions [14]. Later on, experimental wall strengths obtained from available literatures were used to verify the accuracy of the proposed strut and tie model. In addition, strength predictions from building codes [4, 5] and another strut and tie model [15] were included as well for comparison purposes.

RESEARCH SIGNIFICANCE

This study focused on the development of an analytical model based on strut and tie concept to predict RC low rise wall shear strengths. It was expected that the model could serve as a rational yet simple approach for predicting the shear strength of RC low rise walls. Furthermore, the study conducted here provides a new formula for calculating the depth of compression zone at the bottom of RC low rise walls in which the assumption of plane section remains plane (linear strain distribution) does not valid. The formula was developed with the aid of nonlinear finite element analysis using ATENA software [16]. This is important in order to accurately predict the shear strength of RC low rise walls.

BUILDING CODES AND OTHER ANALYTICAL MODEL

The ACI 318 [4] and the Eurocode 8 [5] are two reference building codes that are adopted in many countries. As such, those two building codes and another strut and tie model proposed by other researchers [15] are reviewed briefly below.

ACI 318-14

According to ACI 318-14 [4], the nominal shear strength (V_n) of RC special structural walls can be calculated as follows:

$$V_n = A_{cv}\left(\alpha_c \lambda \sqrt{f_c'} + \rho_t f_y\right) \qquad \text{\{ACI 318-14 Eq. (18.10.4.1)\}}$$

ACI 318-14 also states that the value of V_n shall not exceed $0.83A_{cw}\sqrt{f'_c}$ (in Newton).

Eurocode 8 (EN 1998-1:2004)

According to Eurocode 8 [5] or EC8, the shear strength of RC walls subjected to earthquake loadings can be taken as the lesser value of shear resistance from two failure modes: (1) diagonal compression failure ($V_{Rd,max}$) and (2) diagonal tension failures, either $V_{Rd,s}$ or V_{Rd}.

Diagonal compression failure of the web due to shear

For the case of diagonal compression failure, the shear strength is calculated as follows:

$$V_{Rd,max} = \alpha_{cw} b_w z v_1 f_{cd}/(\cot\theta + \tan\theta) \qquad (1)$$

where:

The recommended value of α_{cw} is as follows:

$$1.0 \text{ for non-prestressed structures} \qquad (1a)$$

$$(1.0 + \sigma_{cp}/f_{cd}) \text{ for } 0 < \sigma_{cp} \leq 0.25 f_{cd} \qquad (1b)$$

$$1.25 \text{ for } 0.25\, f_{cd} < \sigma_{cp} \leq 0.5\, f_{cd} \tag{1c}$$

$$2.5\,(1.0 - \sigma_{cp}/f_{cd}) \text{ for } 0.5\, f_{cd} < \sigma_{cp} < 1.0\, f_{cd} \tag{1d}$$

The recommended value for v_1 is 0.6 [1.0 – f_{ck}/250] (f_{ck} in MPa).

EC8 recommends that the values of cot θ and tan θ are taken as 1.0.

Diagonal tension failure of the web due to shear

If $\alpha_s = M_{Ed}/(V_{Ed}\, L_w) \geq 2.0$, where M_{Ed} is the design bending moment at the base of the wall and V_{Ed} is the design shear force, the shear strength is given by $V_{Rd,s}$:

$$V_{Rd,s} = \frac{A_{sw}}{s} z f_{ywd} \cot\theta \tag{2}$$

If $\alpha_s = M_{Ed}/(V_{Ed}\, L_w) < 2.0$, the shear strength is given by V_{Rd}:

$$V_{Rd} = V_{Rd,c} + 0.75\rho_h f_{yd,h} b_{wo} \alpha_s L_w \tag{3}$$

Hwang-Lee's Model

Hwang and Lee [15] proposed a softened strut and tie model for calculating the shear strength of RC walls. The model has the term "softened" because it takes into account the softening behavior of cracked concrete. In the model, the external forces were resisted by combination of concrete compression struts and steel tension ties as shown in **Fig. 1**. There are three load paths, i.e. vertical, horizontal, and diagonal components which are calculated according to their relative stiffness (R_v, R_h, and R_d) and these components are combined together to become the diagonal compression force acting on nodal zone (C_d). The nominal capacity of the nodal zone can be calculated using Eq. (4a). Then, the shear strength of RC wall according to this model can be taken as the horizontal component of the diagonal compression force that is corresponding to the nominal capacity of the nodal zone.

$$C_{d,n} = K\zeta f_c' A_{str} \tag{4a}$$

where:

K = strut and tie index, which is defined as follows:

$$K = \frac{-D + \frac{F_h}{\cos\theta} + \frac{F_v}{\sin\theta}}{-D + \frac{F_h}{\cos\theta}\left(1 - \frac{\sin^2\theta}{2}\right) + \frac{F_v}{\sin\theta}\left(1 - \frac{\cos^2\theta}{2}\right)} \geq 1.00 \quad (4b)$$

ζ = softening coefficient of cracked diagonal concrete strut, which in this model, it is calculated as $(3.35/\sqrt{f'_c}) \leq 0.52$.

THE PROPOSED STRUT AND TIE MODEL

In this study, an analytical model for predicting RC low rise wall shear strengths was developed based on strut and tie concept. The behavior of RC low rise wall having height to length ratio (H_w/L_w) less than 2.5 is dominated by shear mode [17, 18] and it can be categorized as disturbed region where plane section does not remain plane and shear stress is not uniform within the wall panel. Thus, strut and tie model is considered as a more appropriate approach to predict the strength as compared to sectional design model which includes concrete resistance to shear (V_c) due to tensile stresses in concrete [14, 19]. In contrast to Hwang-Lee's softened strut and tie model [15] that utilizes three compression struts, the model developed in this study utilizes only one diagonal compression strut to be simple.

Equilibrium of the proposed strut and tie model

The internal and external forces equilibrium of the model is displayed on **Fig. 2** and described as follows:

$$P + T = R \quad (5)$$

$$R = C = D\sin\theta \quad (6)$$

$$V = D\cos\theta \quad (7)$$

Initially, a typical RC low rise wall with axial load (P) and lateral load (V) as displayed on **Fig. 2** has reaction forces at the bottom of the wall, i.e. horizontal reaction force that is equal to V, vertical reaction force and bending moment that can be represented by a combination of tension force (T) and compression force (C). In order to simplify the load transfer mechanism, a resultant force (R) is used to replace the axial load (P) and tension force (T) in the equilibrium equation. The resultant force (R) and lateral load (V) are equilibrated at point A by diagonal compression force (D) and thus it forms a strut and tie model. The diagonal compression force (D) is equilibrated at point B by compression force (C) and horizontal reaction force that is equal to V. The governing failure mode of the model is crushing of diagonal compression strut which represents shear failure of the wall web.

Determination of depth of compression zone at the bottom of wall

In this model, depth of compression zone at the bottom of wall (c) as displayed in **Fig. 2** has to be determined first before calculating the diagonal compression strut capacity. Initially, the authors calculated the depth of compression zone (c) based on flexural theory with the assumption of linear strain distribution along wall cross section. Nevertheless, this assumption led to inaccurate predictions of RC wall shear strengths. This was because the assumption might not be valid for RC low rise wall that can be categorized as disturbed region in which plane section does not remain plane. Thus, in this model, the value of c is calculated using a formula that was derived using nonlinear finite element analysis.

Firstly, some parameters that influence the depth of compression zone were identified. Based on flexural theory, these parameters are concrete strength (f'_c), vertical reinforcement area in the edge column or boundary element (A_{sb}), and value of axial load (P). Referring from the flexural theory for member subjected to axial load and bending moment, it is clear that the value of c decreases if the value of f'_c increases. In contrast, the value of c increases if the value of A_{sb} or P increases. Moreover, the authors added shear span ratio or wall height to length ratio (H_w/L_w) as additional parameter that affects the value of c. This was because in similar cases of disturbed region, i.e. deep beams, it was shown that the value of c increases if the shear span ratio decreases [20].

Secondly, after identifying parameters influencing the value of c and their qualitative relationships, the following step was to determine quantitative relationships between these parameters and the value of c. The main objective was to express the value of c as a function of these parameters (f'_c, A_{sb}, P, and H_w/L_w). For this objective, nonlinear finite element analysis was used to determine multiplication factors for each parameter. A typical wall specimen similar to the ones tested by Teng and Chandra [21] was modeled in ATENA software [16]. Then, a parametric study with varying parameters mentioned above was done to obtain the value of c at the peak loading condition of each specimen. For concrete strength, two values were used, i.e. f'_c = 50 MPa (7.25 ksi) and 100 MPa (14.50 ksi). For vertical reinforcement area in the edge column or boundary element, two values were used, i.e. A_{sb} = 1200 mm^2 (1.86 in^2) and 2400 mm^2 (3.72 in^2). For axial force, three values of axial load ratio (ALR) were used, i.e. 0.0, 0.1, and 0.2. For height to length ratio of wall (H_w/L_w), three values were used, i.e. 0.4, 1.0, and 2.0. In addition, the authors also attempted to vary the boundary element width (b_f), i.e. 120 mm (4.72 in), 250 mm (9.84 in), and 500 mm (19.69 in) in order to observe the relationship between c and b_f.

In total, there were 108 specimens analyzed and the values of c obtained at the peak loading condition of each specimen were measured. These values were then plotted against varying parameters to obtain the quantitative relationships. These relationships can be seen in **Figs. 3-5**. The parameters f'_c and P are combined into one to become P/f'_c because this is more frequently used as a parameter. From the figures, it can be seen that the value of c increases linearly with increment of P/f'_c and A_{sb}. In contrast, the value of c decreases exponentially with increment of H_w/L_w. These analysis results are consistent with qualitative relationships mentioned previously. Hence, the value of c can be expressed as follows:

$$c = L_w\left(c_1 + c_2\frac{P}{f_c' A_w} + c_3\frac{A_{sb}}{A_w}\right)\left(\frac{H_w}{L_w}\right)^{c_4} \leq d_w \tag{8}$$

Eq. 8 contains four constants that need to be determined. Constants c_2, c_3, and c_4 can be derived from **Figs. 3-5** by plotting regression lines for each data series. From the equations of the regression lines, the constants are obtained and then the average constant value from 108 data series was calculated. The average regression lines as well as the average constant values are presented in **Fig. 6**. From the figure, the values of c_2, c_3, and c_4 were determined as 0.5, 6.0, and -0.4, respectively. Subsequently, the value of c_1 was obtained by trial and error approach to achieve the most suitable values of c that were in good agreement with the values of c obtained from nonlinear finite element analysis. Thus, the value of c_1 was found to be 0.35. Moreover, from the nonlinear finite element analysis, it was noted that the value of c should not be taken greater than effective depth of wall (d_w). In this model, d_w is defined as the distance of center to center of the edge columns or boundary elements or it can be taken as 80% of wall length ($0.8L_w$) in the case of RC wall without edge columns or boundary elements.

Capacity of diagonal compression strut

Capacity of the diagonal compression strut (D_n) is a product of effective strut strength ($\zeta f'_c$) and the strut area (A_{str}) as described by:

$$D_n = \zeta f_c' A_{str} \tag{9}$$

In this model, the value of effective strut strength is taken as recommended by Eurocode 2 [22]. The code considers reduction of concrete strut strength due to tensile stresses that cause cracks in the concrete strut. Moreover, in this model, increment of concrete strut strength because of confinement effect from transverse reinforcement is also considered using recommendation by FIP Commission 3 [23]. Thus, the softening coefficient for strut strength (ζ) in this model can described as follows:

$$\zeta = 0.6\left(1 - \frac{f_c'}{250}\right) \times 0.80(1 + 1.6\,\alpha_w \omega_w) \leq 0.85 \tag{10}$$

where α_w and ω_w are defined as:

$$\alpha_w = 1.6\frac{s}{t_w} \leq 0.4 \tag{11}$$

$$\omega_w = 4\frac{\rho f_y}{f_c'} \tag{12}$$

Since definition of transverse reinforcement here that provides confinement effect to the concrete strut is the one that is perpendicular to the strut axis, it is needed to represent vertical and horizontal web reinforcement of the RC low rise wall to be the transverse reinforcement of the concrete strut as defined by FIP Commission 3 [23]. Therefore, in this model, the term ρf_y is represented as:

$$\rho f_y = \rho_v f_{yv} \cos\theta + \rho_h f_{yh} \sin\theta \tag{13}$$

where θ is defined as:

$$\theta = \tan^{-1}\left(\frac{H'}{L_w - r - 0.5c}\right) \tag{14}$$

In this model, the value of θ is limited to $31° \leq \theta \leq 59°$.

For the strut area (A_{str}), it is defined as a product of strut depth multiplied by strut width. Strut depth (a_s) is the perpendicular projection of depth of compression zone at the bottom of wall (c) to the strut axis as displayed on **Fig. 2** while strut width can simply be taken as the thickness of wall web (t_w). Finally, the nominal wall shear strength due to crushing of diagonal compression strut (V_n) is defined as:

$$V_n = D_n \cos\theta \tag{15}$$

COMPARISON WITH EXPERIMENTAL RESULTS

To examine the accuracy of the proposed strut and tie model, experimental wall strengths of 100 specimens collected from past experiments on RC low rise walls failing in shear [12, 18, 21, 24-36] were compared with calculated shear strengths from the model. Subsequently, the predictions from the proposed strut and tie model were also compared with predictions from building codes [4, 5] and Hwang and Lee's softened strut and tie model [15]. The analysis results are presented in terms of ratio of the experimental shear strengths to calculated shear strengths (V_{exp}/V_n). The ratio below 1.00 means that the prediction overestimates the shear strength whereas the ratio above 1.00 means that the prediction underestimates the shear strength. These results are presented in **Table 1**. Moreover, the ratio was also plotted against wall height to length ratio (H_w/L_w) (see **Fig. 7**) and concrete compressive strength (f'_c) (see **Fig. 8**) to observe the variation of predictions as affected by those parameters.

From the statistical parameters of V_{exp}/V_n as presented in **Table 1**, it can be concluded that the proposed strut and tie model is quite conservative and the predictions are more accurate than other methods' predictions. The proposed model has the average value V_{exp}/V_n of 1.35 and it has the lowest coefficient of variation (COV) of 0.19 as compared to other methods. It should be noted, nevertheless, that the predictions of the proposed strut and tie model overestimate the shear strength of some specimens tested by Cardenas et al. [18], Cheng et al. [32], and Hube et al. [36]. Furthermore, as can be seen in **Table 1,** Hwang-Lee's model [15] has the average value V_{exp}/V_n of 1.29 which is the closest to 1.00, but it overestimates the shear strength of many RC low rise walls (about 22 out of 100 specimens) whereas the proposed strut and tie model only overestimates 7 out of 100 specimens. Eurocode 8 [5] is indeed the most conservative method with average value V_{exp}/V_n of 2.13

and the code underestimates the shear strength of all 100 specimens collected in this study. Moreover, ACI code [4] has the highest COV of 0.35 with the average value V_{exp}/V_n of 1.41.

From **Figs. 7** and **8**, it can be seen that the predictions of the proposed strut and tie model are uniformly accurate for V_{exp}/V_n with various ranges of wall height to length ratio (H_w/L_w) and concrete compressive strength (f'_c) and they are less scattered as compared to the predictions by other methods. From **Fig. 7**, it can be seen that ACI code [4] is more conservative for walls with lower H_w/L_w while it is the opposite for Hwang-Lee's model [15]. From **Fig. 8**, it can be seen that the predictions of most methods are more conservative for walls with higher f'_c. In addition, the predictions of Eurocode 8 [5] are quite scattered for various ranges of H_w/L_w and f'_c, and there is no clear trend that can be observed from these figures.

CONCLUSIONS

The authors have developed an analytical method based on the strut and tie concept to calculate the shear strength of RC low rise walls. The following conclusions can be made:

1. The proposed strut and tie model was verified with a total of 100 RC low rise walls (H_w/L_w less than 2.5) failing in shear that were selected from available literature [12, 18, 21, 24-36]. The analysis results show that the model is quite conservative and it is reasonably accurate.
2. As compared to building codes [4, 5] and other strut and tie model [15], the predictions of the proposed strut and tie model are more accurate in the sense that it has the average value V_{exp}/V_n of 1.35 with the lowest coefficient of variation of 0.19. The predictions of the proposed model are also quite consistent and less scattered for wide ranges of wall height to length ratios and concrete compressive strengths.

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NOTATION:

A_{cv} = gross area of concrete section bounded by web thickness and length of section in the direction of shear force considered.

A_{cw} = area of concrete section of the individual vertical wall segment considered.

A_g = wall gross cross section area.

a_s = depth of diagonal concrete strut.

A_{sb} = total area of vertical reinforcement in one boundary element.

A_{str} = area of diagonal concrete strut.

A_{sw} = cross sectional area of shear reinforcement.

A_w = wall web area.

b_f = width of boundary element.

b_w = minimum width (thickness) of wall between tension and compression chords.

b_{wo} = width of wall web.

c = depth of compression zone at the bottom of wall.

C = compression force in the compression zone.

C_d = diagonal compression force acting on nodal zone.

$C_{d,n}$ = nominal capacity of the nodal zone.

D = compression force in the diagonal strut.

D_n = nominal strength of diagonal concrete strut.

d_w = effective depth of wall.

f'_c = concrete cylinder compressive strength.

f_{cd} = design value of concrete compressive strength.

f_{ck} = characteristic compressive cylinder strength of concrete at 28 days.

F_h = tension force in the horizontal tie.

F_v = tension force in the vertical tie.

f_y = specified yield strength of reinforcement.

f_{yb} = yield strength of vertical reinforcement in boundary element.

$f_{yd,h}$ = design value of the yield strength of horizontal web reinforcement.

f_{yh} = yield strength of horizontal shear reinforcement.

f_{yv} = yield strength of vertical shear reinforcement.

f_{ywd} = design yield strength of shear reinforcement.

H_w = height of wall.

H' = distance measured from point of application of external shear force to wall base.

K = strut and tie index.

L_w = wall length.

M_{Ed} = design bending moment at the base of the wall.

P = axial load applied at top of wall.

r = distance measured from point of application of resultant force to nearest wall edge.

R = resultant force of external axial force and tension force in tension tie.

R_d = wall shear ratio resisted by diagonal mechanism.

R_h = wall shear ratio resisted by horizontal mechanism.

R_v = wall shear ratio resisted by vertical mechanism.

s = spacing of shear (web) reinforcement.

T = tension force in the tension tie.

t_f = thickness of boundary element.

t_w = thickness of wall web.

V = applied external shear force.

V_c = concrete contribution to overall shear strength.

V_{Ed} = design shear force.

V_{exp} = experimental wall shear strength.

V_n = nominal shear strength of RC wall.

V_{Rd} = shear resistance of a member with shear reinforcement.

$V_{Rd,c}$ = design shear resistance of a member without shear reinforcement.

$V_{Rd,max}$ = design value of the maximum shear force which can be sustained by the member.

$V_{Rd,s}$ = design value of shear force which can be sustained by the yielding shear reinforcement.

z = inner lever arm, which is taken as 0.8 L_w (L_w is wall length).

α = average strut angle with respect to longitudinal (vertical) axis.

α_c = coefficient defining the relative contribution of concrete strength to nominal wall shear strength which may be taken as 0.25 for $H_w/L_w \leq 1.5$, 0.17 for $H_w/L_w \geq 2.0$, and varies linearly between 0.25 and 0.17 for H_w/L_w between 1.5 and 2.0; where H_w/L_w is the height to length ratio of the wall.

α_{cw} = a coefficient taking account of the state of the stress in the compression chord.

α_w = coefficient taking account of confinement effect of web reinforcement to concrete strut strength, related to spacing of web reinforcement.

ζ = softening coefficient of the concrete in compression.

θ = angle between concrete compression strut and wall axis perpendicular to shear force (Eurocode 8).

θ = angle of the diagonal compression strut with respect to the horizontal axis (Hwang-Lee's model and the proposed model).

λ = modification factor reflecting the reduced mechanical properties of lightweight concrete, all relative to normal weight concrete of the same compressive strength.

v_1 = strength reduction factor for concrete cracked in shear.

ρ = reinforcement ratio.

ρ_b = ratio of vertical reinforcement in boundary element.

ρ_h = average horizontal web reinforcement ratio.

ρ_t = ratio of area of distributed transverse (horizontal) shear reinforcement to gross concrete area perpendicular to that reinforcement.

ρ_v = average vertical web reinforcement ratio.

σ_{cp} = mean compressive stress, measured positive, in the concrete due to the design axial force.

ω_w = coefficient taking account of confinement effect of web reinforcement to concrete strut strength, related to ratio of web reinforcement.

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APPENDIX

An example of RC wall shear strength calculation using the authors' proposed strut and tie model is given here. A specimen taken from Teng and Chandra [21] is used, i.e. specimen J5. The procedure is given as follows (in SI unit):

Specimen J5 data:

Concrete compressive strength, f'_c = 103.3 MPa

Wall gross cross section area, A_g = 196000 mm^2

Axial load applied at top of wall, P = 1012 kN (compression)

Wall height, H_w = 2000 mm

Wall length, L_w = 1000 mm

Thickness of wall web, t_w = 100 mm

Width of boundary element, b_f = 500 mm

Thickness of boundary element, t_f = 120 mm

Ratio of vertical reinforcement in boundary element, ρ_b = 0.0388

Yield strength of vertical reinforcement in boundary element, f_{yb} = 630 MPa

Ratio of vertical shear (web) reinforcement in wall, ρ_v = 0.0028

Yield strength of vertical shear reinforcement, f_{yv} = 610 MPa

Ratio of horizontal shear (web) reinforcement in wall, ρ_h = 0.0028

Yield strength of horizontal shear reinforcement, f_{yh} = 610 MPa

Experimental wall shear strength, V_{exp} = 595.76 kN

Calculation of nominal shear strength (V_n) according to the proposed strut and tie model:

1) Calculate c using Eq. 8 and the corresponding A_{str}:

$$c = L_w\left(0.35 + 0.5\frac{P}{f_c' A_w} + 6\frac{A_{sb}}{A_w}\right)\left(\frac{H_w}{L_w}\right)^{-0.4} \leq d_w$$

$$c = 1000\left(0.35 + 0.5\frac{1012000}{103.3 \times 100000} + 6\frac{2328}{100000}\right)\left(\frac{2000}{1000}\right)^{-0.4}$$

$$c = 408.23 \text{ mm} \leq 880 \text{ mm (OK)}$$

Calculating T assuming yielding of reinforcement:

T_1 from vertical reinforcement in boundary element:

$$T_1 = \rho_b \times b_f \times t_f \times f_{yb}$$

$$T_1 = 0.0388 \times 500 \times 120 \times 630$$

$$T_1 = 1466.64 \text{ kN}$$

T_2 from vertical web reinforcement that is in tension:

$$T_2 = \rho_v \times (L_w - c - t_f) \times t_w \times f_{yv}$$

$$T_2 = 0.0028 \times (1000 - 408.23 - 120) \times 100 \times 610$$

$$T_2 = 80.58 \text{ kN}$$

Calculating r by taking wall edge in tension as reference point:

$$r = \frac{T_1 \times \text{arm}_1 + T_2 \times \text{arm}_2 + P \times 0.5L_w}{T_1 + T_2 + P}$$

$$r = \frac{1466.64 \times 0.5 \times 120 + 80.58 \times [120 + 0.5 \times (1000 - 408.23 - 120)] + 1012 \times 500}{1466.64 + 80.58 + 1012}$$

$$r = 243.31 \text{ mm}$$

Calculate θ using Eq. 14:

$$\theta = \tan^{-1}\left(\frac{H'}{L_w - r - 0.5c}\right)$$

$$\theta = \tan^{-1}\left(\frac{2200}{1000 - 243.31 - 0.5 \times 408.23}\right)$$

$$\theta = 75.9°$$

Then, take θ = 59°

Calculating A_{str}:

$$A_{str} = a_s \times t_w$$

$$A_{str} = c \times \sin\theta \times t_w$$

$$A_{str} = 408.23 \times \sin 59° \times 100$$

$$A_{str} = 34992.14 \text{ mm}^2$$

2) Calculate ζ using Eq. 10:

Calculating α_w using Eq. 11:

$$\alpha_w = 1.6\frac{s}{t_w} \leq 0.4$$

$$\alpha_w = 1.6\frac{200}{100}$$

$$\alpha_w = 3.2$$

Then, take $\alpha_w = 0.4$

Calculating ω_w using Eq. 12:

$$\rho f_y = \rho_v f_{yv} \cos\theta + \rho_h f_{yh} \sin\theta$$

$$\rho f_y = 0.0028 \times 610 \times \cos 59° + 0.0028 \times 610 \times \sin 59°$$

$$\rho f_y = 2.34$$

$$\omega_w = 4\frac{\rho f_y}{f_c'}$$

$$\omega_w = 4\frac{2.34}{103.3}$$

$$\omega_w = 0.09$$

$$\zeta = 0.6\left(1 - \frac{f_c'}{250}\right) \times 0.80(1 + 1.6\ \alpha_w \omega_w) \leq 0.85$$

$$\zeta = 0.6\left(1 - \frac{103.3}{250}\right) \times 0.80(1 + 1.6 \times 0.4 \times 0.09)$$

$$\zeta = 0.30$$

3) Calculate D_n using Eq. 9:

$$D_n = \zeta f_c' A_{str}$$

$$D_n = 0.30 \times 103.3 \times 34992.14$$

$$D_n = 1077.18\ \text{kN}$$

4) Calculate V_n using Eq. 15:

$$V_n = D_n \cos\theta$$

$$V_n = 1077.18 \times \cos 59°$$

$$V_n = 554.79\ \text{kN}$$

Thus, V_{exp}/V_n = 595.76/554.79 = 1.07

TABLES AND FIGURES

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Fig. 3 *– Values of c/L_w obtained from nonlinear finite element analysis plotted against $P/[f'_c A_w]$; (a) cases for b_f = 120 mm (4.72 in), (b) cases for b_f = 250 mm (9.84 in), and (c) cases for b_f = 500 mm (19.69 in).*

Fig. 4 *– Values of c/L_w obtained from nonlinear finite element analysis plotted against A_{sb}/A_w; (a) cases for b_f = 120 mm (4.72 in), (b) cases for b_f = 250 mm (9.84 in), and (c) cases for b_f = 500 mm (19.69 in).*

Fig. 5 *– Values of c/L_w obtained from nonlinear finite element analysis plotted against H_w/L_w; (a) cases for b_f = 120 mm (4.72 in), (b) cases for b_f = 250 mm (9.84 in), and (c) cases for b_f = 500 mm (19.69 in).*

Fig. 6 – *Relationships between c and varying parameters with the average regression lines and their equations.*

Fig. 7 *– V_{exp}/V_n plotted against wall height to length ratio (H_w/L_w).*

Fig. 8 *– V_{exp}/V_n plotted against concrete compressive strength (f'_c).*

Table 1–Ratio of experimental and calculated wall shear strengths

No.	Specimen ID	f'_c (MPa)	H_w/L_w	V_{exp}/V_n			
				ACI 318 [4]	Eurocode 8 [5]	Hwang-Lee [15]	Proposed Model
Hirosawa [24]							
1	72	17	0.94	1.33	1.71	1.13	1.42
2	73	21	0.94	1.28	1.68	1.00	1.28
3	74	21	0.94	0.82	1.45	1.01	1.17
4	75	14	0.94	0.97	2.09	1.39	1.47
5	76	15	0.94	0.92	1.94	1.30	1.16
6	77	18	0.94	0.91	1.78	1.23	1.18
7	79	14	0.94	0.71	1.52	1.01	1.09
8	82	21	1.88	0.72	1.22	0.95	1.20
9	83	18	1.88	0.70	1.26	1.02	1.25
Barda et al. [25]							
10	B1-1	29	0.46	1.65	3.94	1.23	1.52
11	B2-1	16	0.46	1.51	3.45	1.72	1.39
12	B3-2	27	0.46	1.48	3.23	1.18	1.29
13	B6-4	21	0.46	1.25	2.72	1.39	1.33
14	B7-5	26	0.21	1.56	4.64	1.09	1.11
15	B8-5	23	0.96	1.24	2.24	1.82	1.57
Cardenas et al. [18]							
16	SW-7	43	1.00	1.30	2.06	0.88	1.03
17	SW-8	42	1.00	1.36	2.02	0.97	0.96
Corley et al. [26]							
18	B2	54	2.40	0.76	1.31	1.04	1.04
19	B5	45	2.40	0.91	1.56	1.27	1.30
20	B6	22	2.40	1.10	1.96	1.56	1.78
21	B7	49	2.40	1.18	2.05	1.11	1.40
22	B8	42	2.40	0.94	1.38	1.13	1.31
23	B9	44	2.40	1.25	2.17	1.12	1.49
24	B10	46	2.40	0.90	1.56	0.81	1.17
25	F1	38	2.40	0.90	1.45	1.41	1.51
26	F2	46	2.40	1.13	1.96	0.91	1.28
Maeda [27]							
27	MAE03	58	0.55	1.46	2.82	1.02	1.09
28	MAE07	58	0.55	1.52	2.38	1.10	1.11
Okamoto [28]							
29	W48M6	82	0.74	1.10	1.99	0.88	1.16
30	W48M4	82	0.74	1.12	1.97	0.86	1.14
31	W72M8	82	0.74	1.33	1.89	1.20	1.41
32	W72M6	82	0.74	1.30	1.93	1.17	1.38
33	W72M8	102	0.74	1.23	1.93	1.14	1.40
34	W96M8	102	0.74	1.44	2.04	1.33	1.49
Gupta and Rangan [12]							
35	S-1	79	1.00	1.11	1.58	0.99	1.03
36	S-2	65	1.00	1.96	2.24	1.32	1.55
37	S-3	69	1.00	2.28	2.28	1.23	1.53

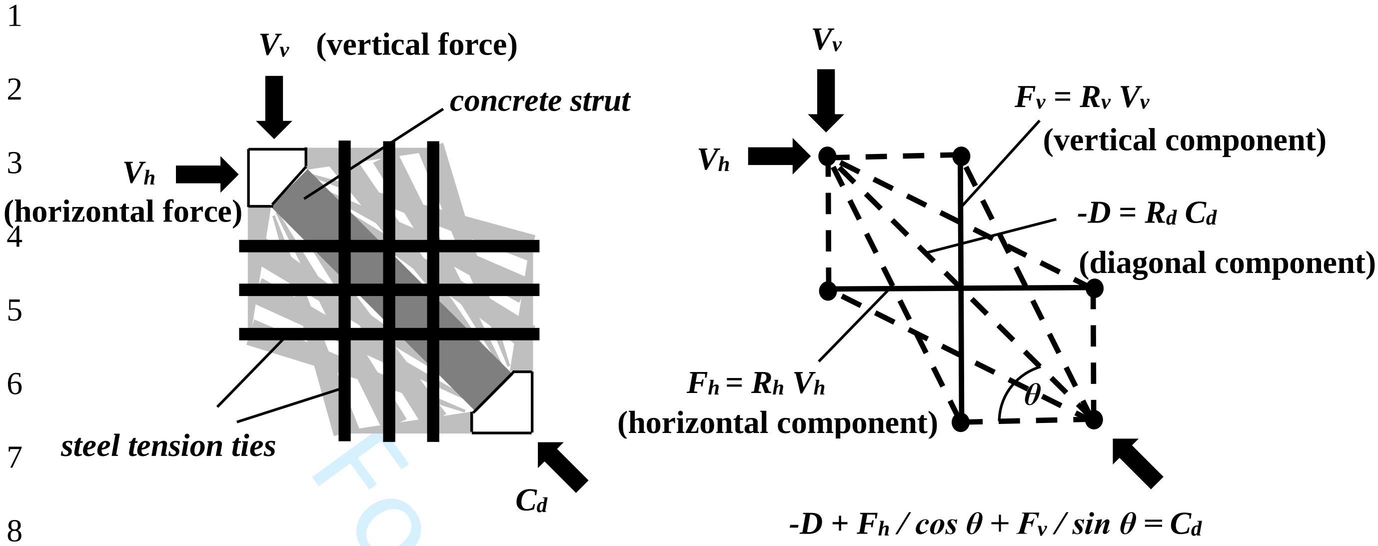
1 **Table 1–Ratio of experimental and calculated wall shear strengths (continued)**

No.	Specimen ID	f'_c (MPa)	H_w/L_w	V_{exp}/V_n ACI 318 [4]	Eurocode 8 [5]	Hwang-Lee [15]	Proposed Model
38	S-4	75	1.00	1.58	2.16	1.43	1.32
39	S-5	73	1.00	2.10	2.43	1.42	1.49
40	S-6	71	1.00	2.59	2.60	1.40	1.62
41	S-7	71	1.00	1.52	2.05	1.41	1.56
Kabeyasawa and Hiraishi [29]							
42	W-08	103	1.18	1.48	1.93	1.35	1.89
43	W-12	138	1.18	1.46	1.95	1.21	1.99
44	No. 1	65	1.18	2.25	2.19	1.11	1.48
45	No. 2	71	1.18	1.90	1.93	1.18	1.55
46	No. 3	72	1.18	1.60	1.84	1.23	1.59
47	No. 4	103	1.18	1.84	1.88	1.22	1.70
48	No. 5	77	1.76	1.41	1.50	1.07	1.55
49	No. 6	74	1.18	1.45	1.86	1.26	1.34
50	No. 7	72	1.18	1.57	2.01	1.34	1.50
51	No. 8	76	1.18	1.66	2.13	1.45	1.45
Farvashany et al. [30]							
52	HSCW1	104	1.25	2.20	2.36	1.56	1.62
53	HSCW2	93	1.25	2.60	2.48	1.60	1.78
54	HSCW3	86	1.25	1.96	1.85	1.19	1.38
55	HSCW4	91	1.25	2.68	1.99	1.13	1.56
56	HSCW5	84	1.25	1.93	2.07	1.42	1.66
57	HSCW6	90	1.25	1.77	1.94	1.49	1.63
58	HSCW7	102	1.25	1.85	1.94	1.39	1.67
Burgueno et al. [31]							
59	M05C	46	2.25	1.85	2.68	2.46	1.62
60	M05M	39	2.25	2.14	3.23	2.76	1.81
61	M10C	56	2.25	1.56	2.19	2.22	1.39
62	M10M	84	2.25	1.53	2.09	2.43	1.51
63	M15C	102	2.25	1.27	1.77	2.09	1.37
64	M15M	111	2.25	1.38	1.98	2.33	1.54
65	M20C	131	2.25	1.11	1.72	1.92	1.35
66	M20M	115	2.25	1.34	1.95	2.27	1.49
Cheng et al. [32]							
67	M60	39	0.94	0.92	1.76	0.69	0.93
68	M115	38	0.94	0.68	1.14	0.68	0.83
69	H60	44	0.94	0.87	1.37	1.08	1.12
70	H115	44	0.94	0.88	1.39	0.99	1.13
71	H60X	42	0.94	0.88	1.41	1.10	1.14
Teng and Chandra [21]							
72	J1	103	1.00	2.85	3.25	1.62	1.65
73	J2	97	1.00	3.05	3.48	1.75	1.71
74	J3	111	1.00	2.09	2.36	1.71	1.87
75	J4	94	1.00	1.97	2.35	1.44	1.19
76	J5	103	2.00	1.73	4.36	1.07	1.07

Table 1–Ratio of experimental and calculated wall shear strengths (continued)

No.	Specimen ID	f'_c (MPa)	H_w/L_w	V_{exp}/V_n			
				ACI 318 [4]	**Eurocode 8 [5]**	**Hwang-Lee [15]**	**Proposed Model**
77	J6	97	2.00	2.14	5.30	1.33	1.29
78	J7	111	2.00	1.46	2.58	1.23	1.52
Baek et al. [33]							
79	NS2	37	2.00	1.34	2.10	1.98	1.72
80	HS2	37	2.00	1.30	2.04	1.93	1.72
81	NS2L	37	2.00	1.40	2.57	1.31	1.43
82	HS2L	37	2.00	1.45	2.63	1.41	1.54
Baek et al. [34]							
83	NS1M	53	1.00	1.26	1.77	1.37	1.31
84	HS1M	53	1.00	1.17	1.64	1.28	1.22
85	NS0.5M	45	0.50	1.50	2.33	1.19	1.25
86	HS0.5M	37	0.50	1.54	2.40	1.29	1.29
Baek et al. [35]							
87	SW1	20	2.50	0.91	1.90	1.36	1.30
88	SW2	20	2.50	1.14	2.36	0.92	1.28
89	SW3	20	2.50	0.90	1.90	1.30	1.21
90	SW4	20	2.50	1.17	2.48	0.92	1.26
91	SW5	37	2.50	1.20	2.86	0.79	1.06
92	SW6	37	2.50	1.21	2.95	0.79	1.02
Hube et al. [36]							
93	WSL1	29	1.00	0.85	1.31	0.77	0.87
94	WSL3	29	1.00	1.01	1.50	1.02	1.13
95	WSL4	29	1.00	1.13	1.80	0.92	1.03
96	WSL5	29	1.00	1.00	1.58	0.82	0.91
97	WSL6	29	1.00	1.12	1.86	0.84	0.92
98	WSL7	29	1.00	0.89	1.34	0.87	1.00
99	WSL8	29	1.00	0.94	1.49	0.80	0.93
100	WSL9	29	1.00	1.07	1.67	0.92	1.07
Statistical Parameters							
Minimum Value				0.68	1.14	0.68	0.83
Maximum Value				3.05	5.30	2.76	1.99
Average Value				1.41	2.13	1.29	1.35
Standard Deviation				0.50	0.70	0.41	0.25
Coefficient of Variation				0.35	0.33	0.32	0.19

Note: 1 MPa = 145.04 psi.



(a) Disturbed stress field *(b) Strut and tie idealization*

Fig. 1–Strut and tie mechanisms proposed by Hwang and Lee [15].

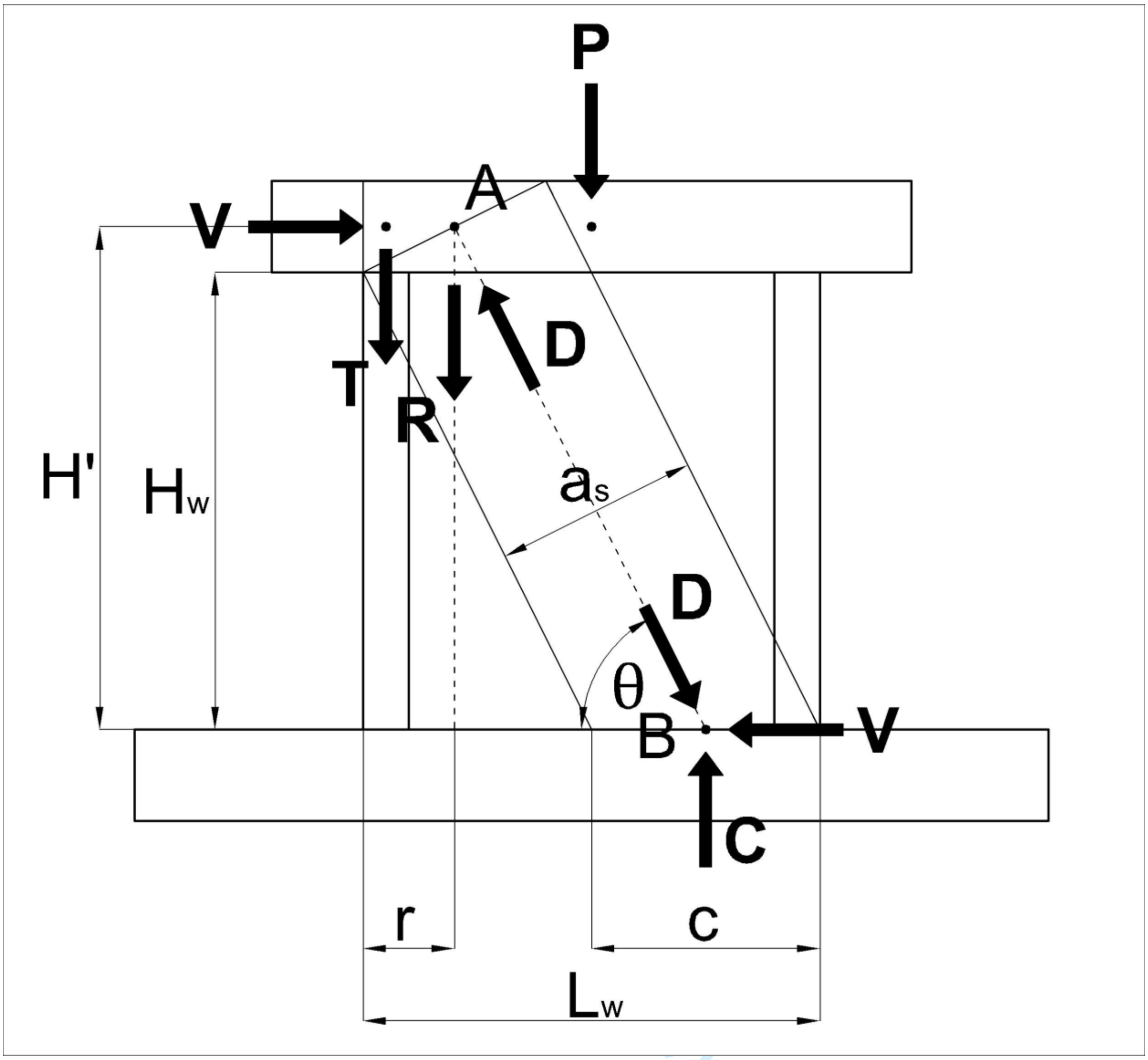
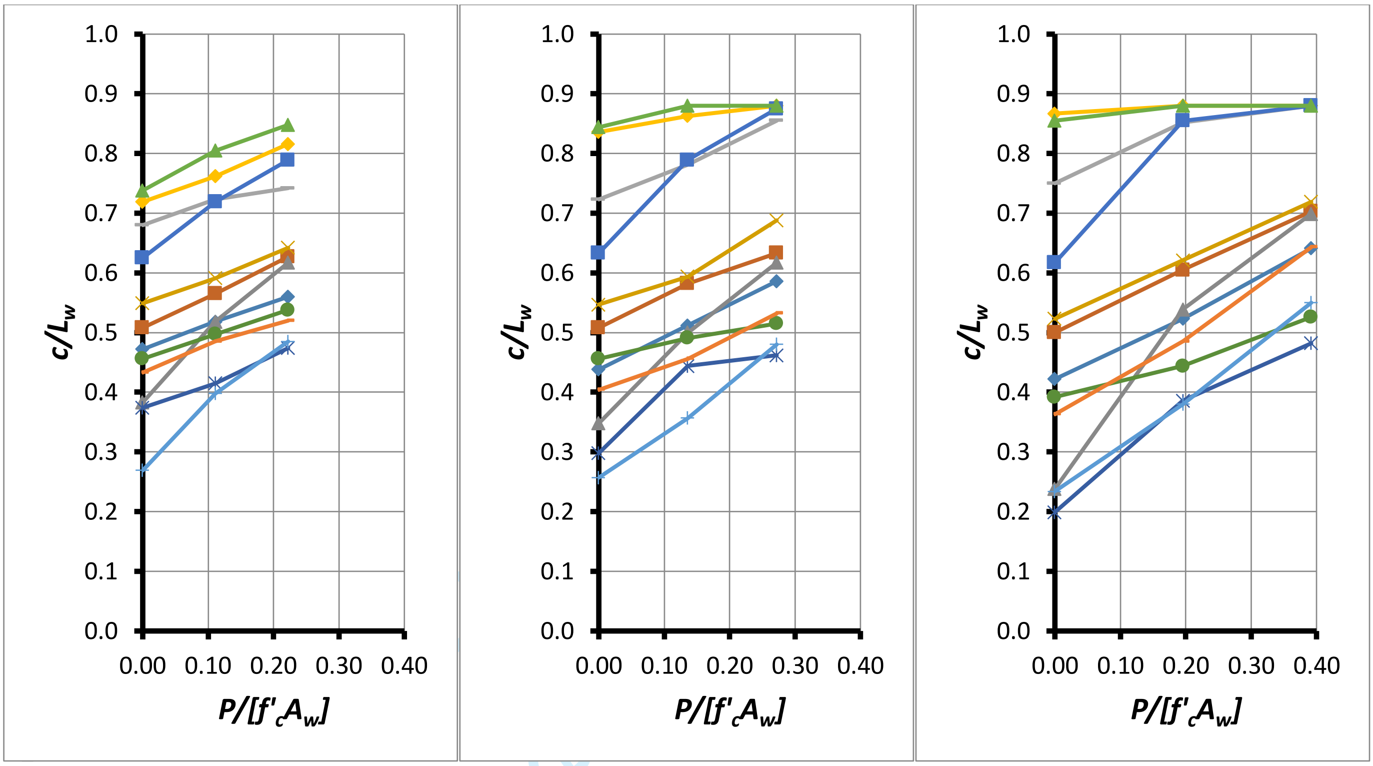
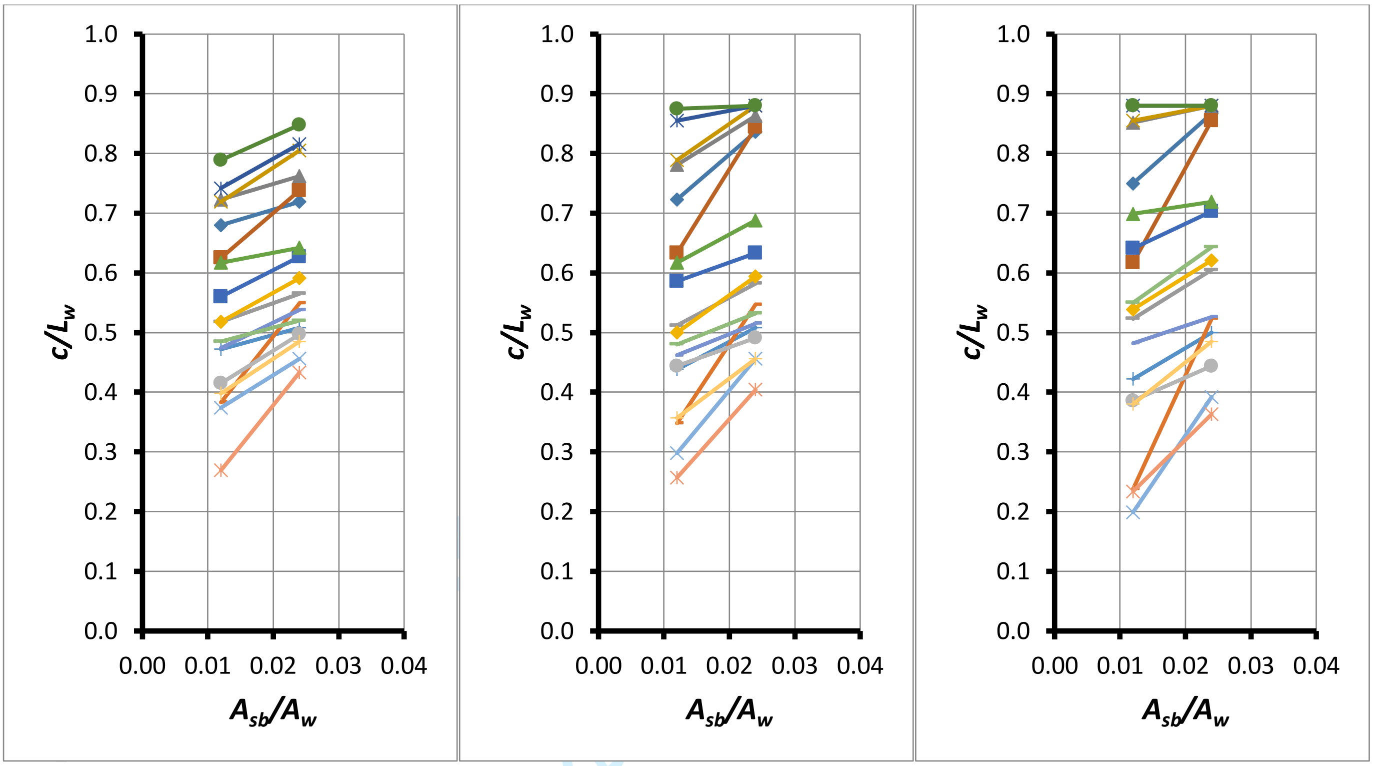


Fig. 2–Equilibrium of the proposed strut and tie model.



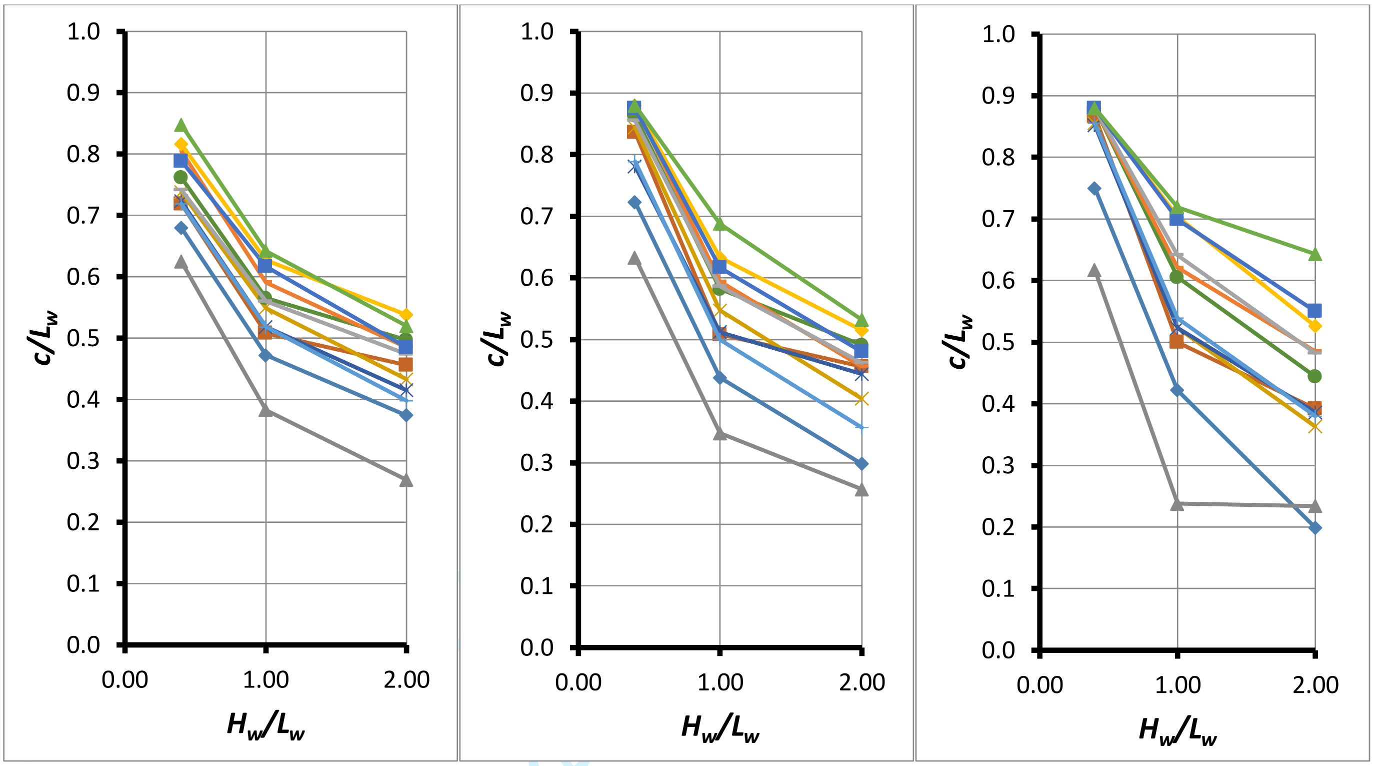
(a) (b) (c)

Fig. 3–Values of c/L_w *obtained from nonlinear finite element analysis plotted against* $P/[f'_cA_w]$*; (a) cases for* b_f *= 120 mm (4.72 in), (b) cases for* b_f *= 250 mm (9.84 in), and (c) cases for* b_f *= 500 mm (19.69 in).*



(a) (b) (c)

Fig. 4–Values of c/L_w obtained from nonlinear finite element analysis plotted against A_{sb}/A_w; (a) cases for b_f = 120 mm (4.72 in), (b) cases for b_f = 250 mm (9.84 in), and (c) cases for b_f = 500 mm (19.69 in).



(a) (b) (c)

Fig. 5–Values of c/L_w obtained from nonlinear finite element analysis plotted against H_w/L_w; (a) cases for b_f = 120 mm (4.72 in), (b) cases for b_f = 250 mm (9.84 in), and (c) cases for b_f = 500 mm (19.69 in).

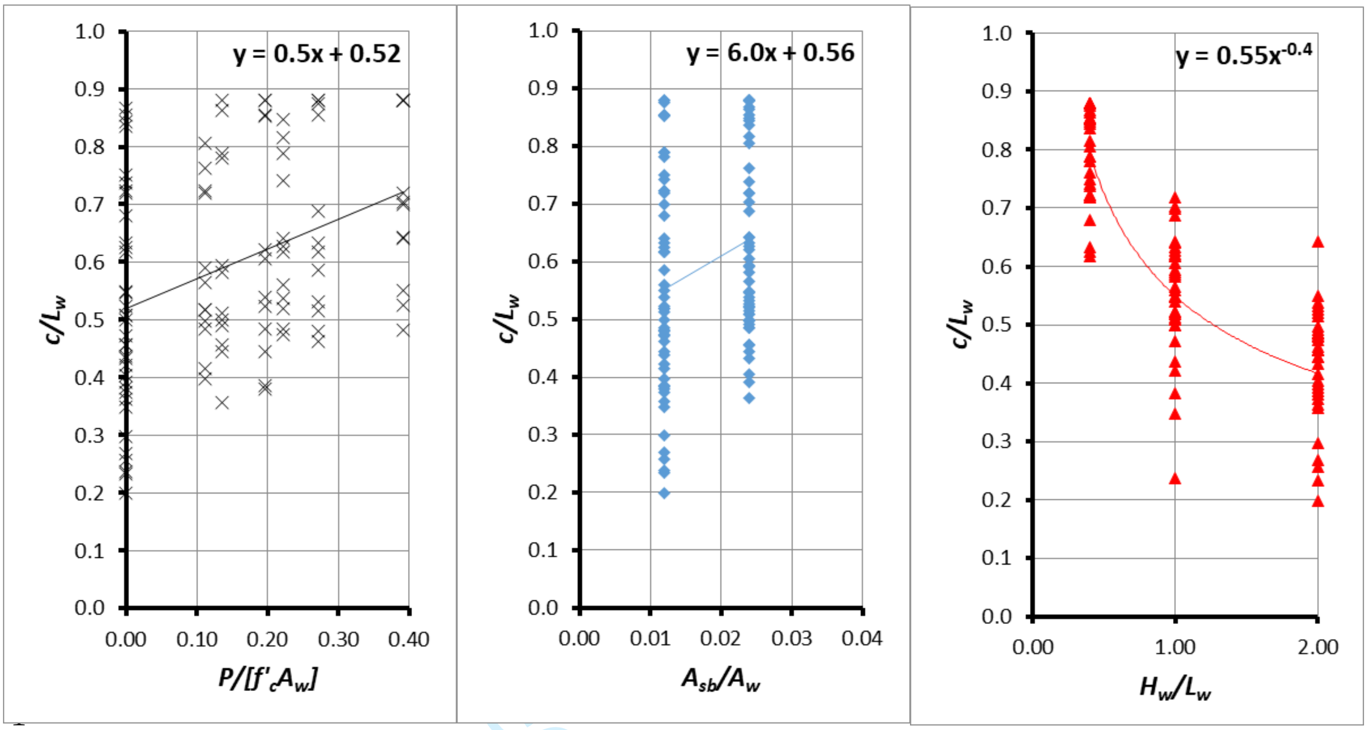


Fig. 6–Relationships between c and varying parameters with the average regression lines and their equations.

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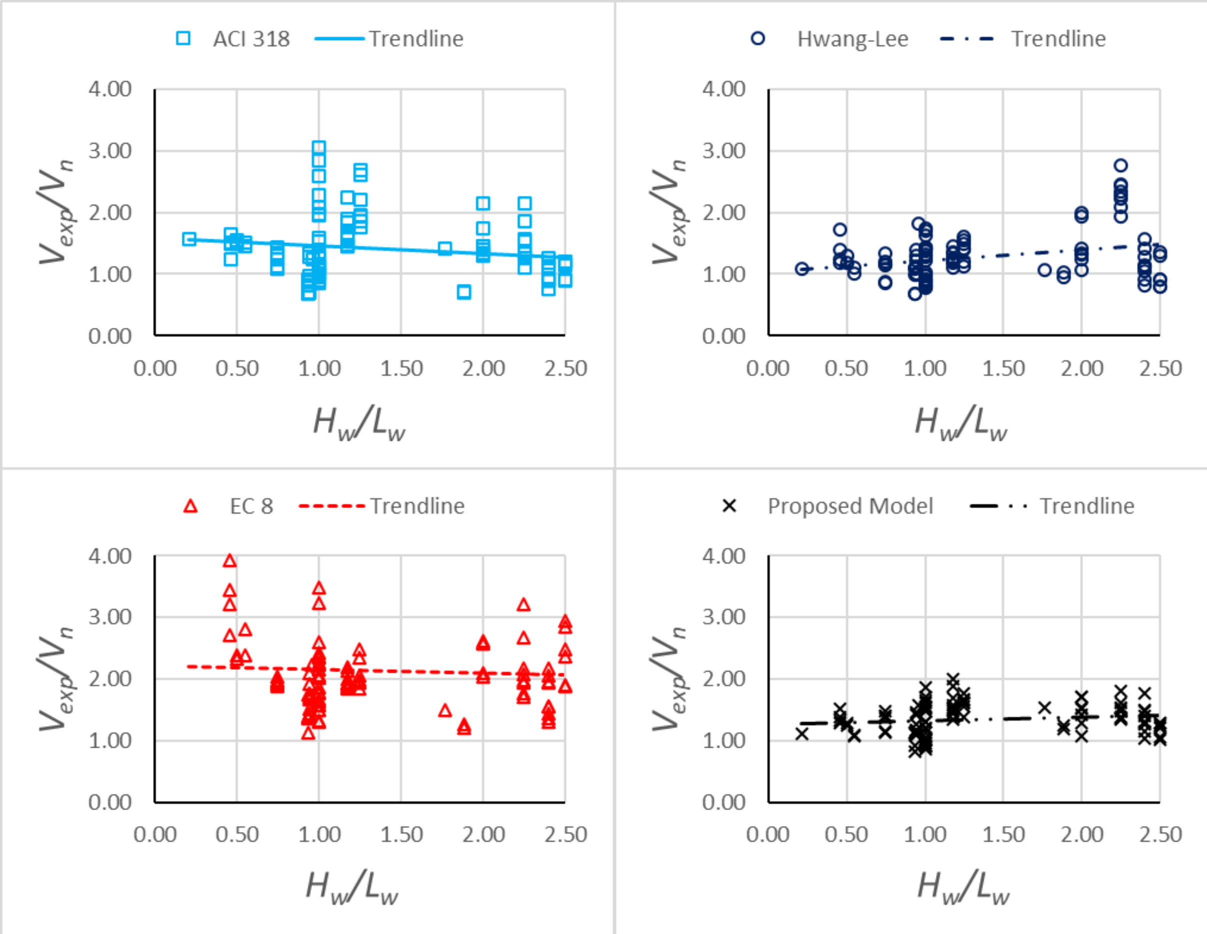
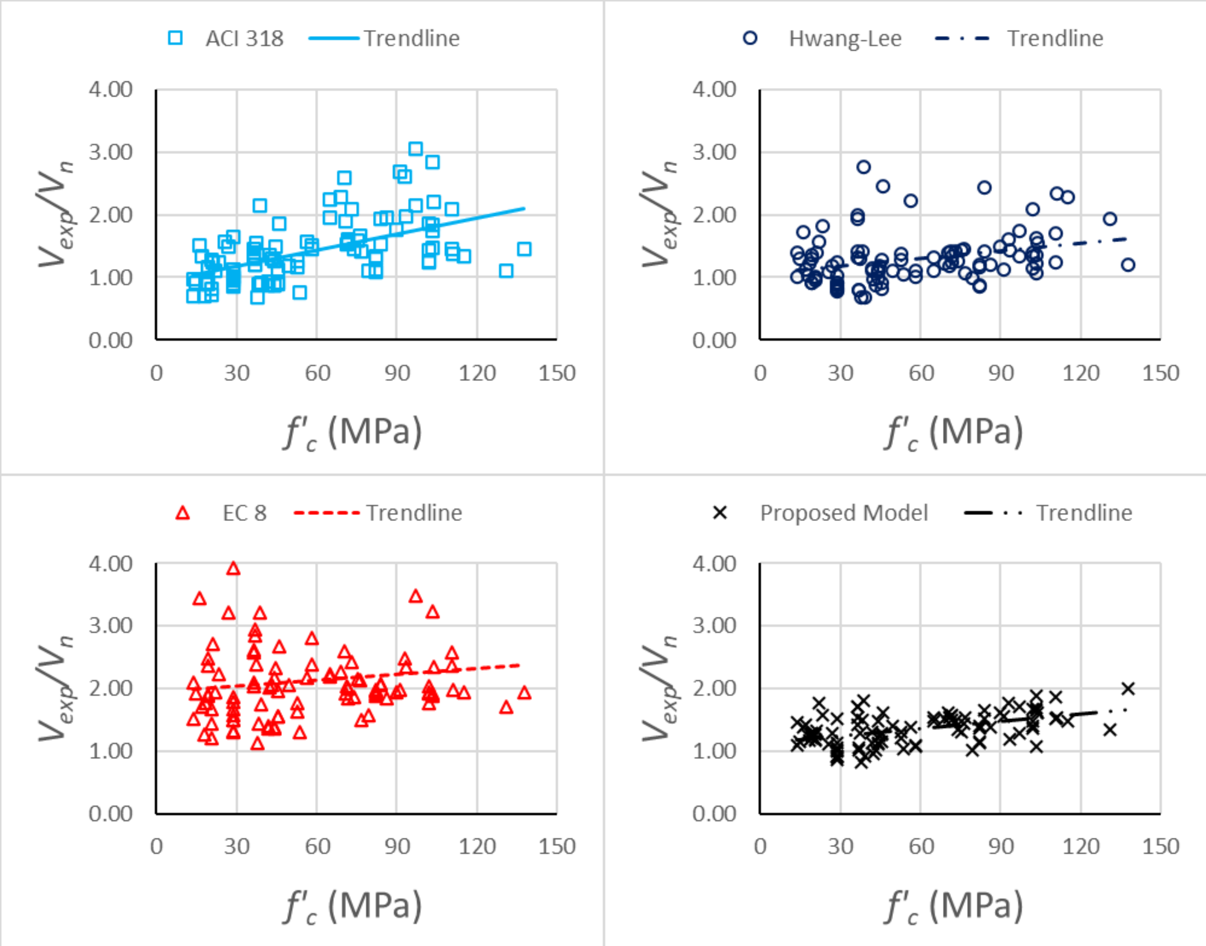


2 *Fig. 7–V_{exp}/V_n plotted against wall height to length ratio (H_w/L_w).*

3

See the sticky notes for comments.

1 

2 *Fig. 8–V_{exp}/V_n plotted against concrete compressive strength (f'_c).*

3 *Note: 1 MPa = 145.04 psi.*

4

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Thank you for your contribution to the ACI Journals.

Sincerely,

Ms Angela Matthews

Jimmy Chandra <chandra.jimmy@petra.ac.id> Wed, Oct 13, 2021 at 7:54 AM
To: Journals.manuscripts@concrete.org

Dear Ms Angela Matthews,

Thank you very much for the acceptance of our paper.

I have a few questions regarding the final submission of the paper:
1. Since the paper is accepted to be published in its present form, do I need to submit our responses to the reviewers' comments?
2. For the copyright transfer form, my second author (Dr. Susanto Teng) has passed away. I am afraid that I will not be able to get his signature for the form. In this case, what do you suggest? Is it okay to submit the form with my signature only as the first author?

I look forward for your kind response. Thank you very much for your attention.

Best regards,

Jimmy

[Quoted text hidden]

ACI Journal Review <Journals.Manuscripts@concrete.org> Wed, Oct 13, 2021 at 7:45 PM
To: Jimmy Chandra <chandra.jimmy@petra.ac.id>

Dear Dr Jimmy Chandra,

Thank you for your email.

1. It is not necessary to address review comments unless you feel they are valuable to your manuscript.
2. I am sorry to hear Dr. Teng has passed away. Yes, you may submit the form with your name only.

Congratulations on your fine manuscript!

[Quoted text hidden]

Jimmy Chandra <chandra.jimmy@petra.ac.id> Thu, Oct 21, 2021 at 5:25 PM
To: ACI Journal Review <Journals.Manuscripts@concrete.org>, manuscripts.final@concrete.org

Dear Ms Angela Matthews and Ms Susan Esper,

Here as attached are the manuscript files (Word and PDF format) and the copyright transfer form with my signature only as the first author since the second author of the paper (Dr. Susanto Teng) has passed away, thus unable to sign the form.

Let me know if there is anything else I have to submit. Thank you very much.

Best regards,

Jimmy
[Quoted text hidden]

---

3 attachments

Copyright-Transfer-Form.pdf
186K

Manuscript'.docx
1055K

Manuscript'.pdf
1113K

5. Submission final (21 Oktober 2021)

ACI Structural and Materials Journals

Preview (S-2020-477.R1)

From: manuscripts.final@concrete.org

To: chandra.jimmy@petra.ac.id

CC:

Subject: S-2020-477.R1 - Simplified Strut and Tie Model for Shear Strength Prediction of Reinforced Concrete Low Rise Walls

Body: 21-Oct-2021

S-2020-477.R1 - Simplified Strut and Tie Model for Shear Strength Prediction of Reinforced Concrete Low Rise Walls

Dear Dr Jimmy Chandra:

ACKNOWLEDGMENT OF FINAL MANUSCRIPT

Thank you for your final manuscript submission, which we received on 21 October 2021. It will be published in a future issue of the ACI Structural/Materials Journal.

Please know your manuscript has been passed on to the Publishing Services Department, which will be preparing it for publication. No definite date for publication can be ascertained at this time. When the editors begin work on your manuscript, you will receive an "author galley" prior to the manuscript being published in the journal. This allows you to check over the proof and indicate any needed corrections. After the issue is published, you along with any co-authors will receive a complimentary Acrobat PDF of the issue.

If you have any questions regarding your manuscript, or if you wish to notify the editors regarding an address change or other information, please contact Tiesha Elam at Tiesha.Elam@concrete.org for the ACI Structural Journal or Kaitlyn Dobberteen at Kaitlyn.Dobberteen@concrete.org for the ACI Materials Journal. In future correspondence, please continue to refer to your manuscript in the e-mail subject line by its assigned ID number given when it was accepted (S-2020-477.R1).

Sincerely,
Ms Susan Esper

Date Sent: 21-Oct-2021

Close Window

UNIVERSITAS KRISTEN PETRA

Jimmy Chandra <chandra.jimmy@petra.ac.id>

S-2020-477.R1 - Simplified Strut and Tie Model for Shear Strength Prediction of Reinforced Concrete Low Rise Walls

ACI Structural and Materials Journals <onbehalfof@manuscriptcentral.com> Fri, Oct 22, 2021 at 12:38 AM
Reply-To: manuscripts.final@concrete.org
To: chandra.jimmy@petra.ac.id

21-Oct-2021

S-2020-477.R1 - Simplified Strut and Tie Model for Shear Strength Prediction of Reinforced Concrete Low Rise Walls

Dear Dr Jimmy Chandra:

ACKNOWLEDGMENT OF FINAL MANUSCRIPT

Thank you for your final manuscript submission, which we received on 21 October 2021. It will be published in a future issue of the ACI Structural/Materials Journal.

Please know your manuscript has been passed on to the Publishing Services Department, which will be preparing it for publication. No definite date for publication can be ascertained at this time. When the editors begin work on your manuscript, you will receive an “author galley” prior to the manuscript being published in the journal. This allows you to check over the proof and indicate any needed corrections. After the issue is published, you along with any co-authors will receive a complimentary Acrobat PDF of the issue.

If you have any questions regarding your manuscript, or if you wish to notify the editors regarding an address change or other information, please contact Tiesha Elam at Tiesha.Elam@concrete.org for the ACI Structural Journal or Kaitlyn Dobberteen at Kaitlyn.Dobberteen@concrete.org for the ACI Materials Journal. In future correspondence, please continue to refer to your manuscript in the e-mail subject line by its assigned ID number given when it was accepted (S-2020-477.R1).

Sincerely,
Ms Susan Esper

6. **Pengecekan author galley sebelum terbit dan koreksinya (10-14 Februari 2022)**

UNIVERSITAS KRISTEN PETRA

Jimmy Chandra <chandra.jimmy@petra.ac.id>

Author galley for manuscript S-2020-477.R1 to be published in the ACI Structural Journal

6 messages

Kaitlyn J. Dobberteen <Kaitlyn.Dobberteen@concrete.org> Thu, Feb 10, 2022 at 2:06 AM
To: "chandra.jimmy@petra.ac.id" <chandra.jimmy@petra.ac.id>

Dear Jimmy Chandra—

INSTRUCTIONS TO AUTHOR

Confirm receipt

We ask that you please acknowledge receipt of this e-mail.

Answering queries

Queries are embedded within the attached PDF file on page 13. Please note: the queries are yellow bubbles. Answers to these queries and any additional comments can also be embedded within the PDF file. Click on the yellow query, then click "Options," then click "Reply." Do not color code your answers or comments within the PDF file.

If you are unable to embed your answers and/or comments, corrections can be made by e-mailing or faxing a marked-up hard copy. Please print legibly in dark ink. Do not use pencil or a highlighter.

Before submitting the author galley

In addition to answering the queries, please submit an itemized list of the corrections in a PDF or Word file. At this time, we also ask that you verify that the author email address(es) are listed correctly in ACI's ScholarOne Manuscript Center and/or send all author email address(es) along with the completed galley for electronic distribution of the journal.

Deadline

Once you have completed the above steps, return your author galley via e-mail to: Ms. Kaitlyn Dobberteen at Kaitlyn.Dobberteen@concrete.org. Corrections must be submitted by Tuesday, February 15, 2022, or sooner if possible. ACI reserves the right to move manuscripts to a future issue if galleys are not returned by the deadline.

Additional information

Please be advised you are the only recipient of this galley and only your corrections will be incorporated in the final manuscript that is published. When you are reading this proof, please note that only corrections of errors can be made at this stage of production. Extensive revisions cannot be made except to correct a technical error. If such an error has been made and a paragraph MUST be revised, please keep in mind that any correction you may suggest must fit the space allocated for the replaced copy. Editorial revisions may have been made by the ACI editors to conform to ACI publication style or policy.

If you have any style/layout questions, please contact Kaitlyn Dobberteen, by phone at +1.248.848.3819, or e-mail at Kaitlyn.Dobberteen@concrete.org.

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If you have any questions or concerns, please feel free to contact Ms. Kaitlyn Dobberteen. Thank you for your cooperation.

Kaitlyn Dobberteen
Editor, Publishing Services

p +1.248.848.3819

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20-477.pdf
3986K

Jimmy Chandra <chandra.jimmy@petra.ac.id> Thu, Feb 10, 2022 at 5:09 PM
To: "Kaitlyn J. Dobberteen" <kaitlyn.dobberteen@concrete.org>

Dear Ms. Kaitlyn,

Thank you for the author galley. I will submit a list of corrections in the next email as soon as possible.

Thanks and regards,

Jimmy
[Quoted text hidden]

Jimmy Chandra <chandra.jimmy@petra.ac.id> Sat, Feb 12, 2022 at 3:50 PM
To: "Kaitlyn J. Dobberteen" <kaitlyn.dobberteen@concrete.org>

Dear Ms. Kaitlyn J. Dobberteen,

Here as attached is the author galley PDF file with my comments for corrections. I also attached an MS word file that consists of a list of corrections for the manuscript. Please acknowledge if you have received those files and let me know if you have any questions.

Furthermore, I would like to request an electronic copy of the published article later, if possible, for posting it in my University's repository. With this email, I also would like to ask permission from ACI to do so.

Thank you very much.

Best regards,

Jimmy

On Thu, Feb 10, 2022 at 2:06 AM Kaitlyn J. Dobberteen <Kaitlyn.Dobberteen@concrete.org> wrote:
[Quoted text hidden]

2 attachments

Corrections List for Manuscript 20-477.docx
16K

20-477.pdf
3846K

Kaitlyn J. Dobberteen <Kaitlyn.Dobberteen@concrete.org> Mon, Feb 14, 2022 at 8:10 PM
To: Jimmy Chandra <chandra.jimmy@petra.ac.id>
Cc: Angela Noelker <Angela.Noelker@concrete.org>

Jimmy—

Thanks for getting this back to us! The changes have been made and your paper is ready to appear in the next issue of the journal.

As to your second request, I'm including Angela Noelker on this email, as she'll be able to better answer your question as far as reposting permission.

Have a great day!

Kaitlyn Dobberteen
Editor, Publishing Services

p +1.248.848.3819

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[Quoted text hidden]

Angela Noelker <Angela.Noelker@concrete.org> Mon, Feb 14, 2022 at 8:14 PM
To: "Kaitlyn J. Dobberteen" <Kaitlyn.Dobberteen@concrete.org>, Jimmy Chandra <chandra.jimmy@petra.ac.id>

Dear Dr Jimmy Chandra,

Thank you for your email. You may certainly post your work to the repository free of charge. It is not necessary to obtain ACI's permission.

Sincerely,

Angela Noelker
Editor
Angela.Noelker@concrete.org

38800 Country Club Drive
Farmington Hills, MI 48331

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[Quoted text hidden]

Jimmy Chandra <chandra.jimmy@petra.ac.id> Tue, Feb 15, 2022 at 1:07 AM
To: Angela Noelker <Angela.Noelker@concrete.org>
Cc: "Kaitlyn J. Dobberteen" <Kaitlyn.Dobberteen@concrete.org>

Dear Ms. Angela and Ms. Kaitlyn,

Thank you very much for your answer and replies.

Best regards,

Jimmy
[Quoted text hidden]

Corrections List for Manuscript 20-477:

1. Page 5, Fig. 6 caption.

   Sentence:

   "*Fig. 6—Values of* c/Lw *obtained from nonlinear finite element analysis plotted against* Asb/Aw*: (a) cases for* bf *= 120 mm (4.72 in.); (b) cases for* bf *= 250 mm (9.84 in.); and (c) cases for* bf *= 500 mm (19.69 in.)*."

   Correction:

   We would like to change the words "finite element analysis" into "FEA".

2. Page 6, left column, first paragraph.

   Sentence:

   "From the equations of the regression lines, the constants are obtained and then the average constant value from 108 data series was calculated."

   Correction:

   We would like to change the words "are" into "were" and "108" into "all".

3. Page 7, left column, equation 9.

   Formula:

   "$Dn = \xi f c' Astr$"

   Correction:

   We would like to change the symbol "ξ" into "ζ".

4. Page 13, left column, Appendix.

   Question:

   No appendix callout appears in the body of the paper; where should one appear?

   Answer:

   We can add a new sentence below equation 15 (before COMPARISON WITH EXPERIMENTAL RESULTS part).

   The new sentence is as follow:

“An example of RC wall shear strength calculation using the proposed strut-and-tie model can be seen in Appendix.”