DETERMINATION OF EFFECTIVE BREADTH WIDTH OF STIFFENED STEEL PLATE STRUCTURES BASED ON NONLINEAR FINITE ELEMENT ANALYSIS

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DETERMINATION OF EFFECTIVE BREADTH WIDTH OF STIFFENED STEEL PLATE STRUCTURES BASED ON NONLINEAR FINITE ELEMENT ANALYSIS

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Dedicated to

My Lovely Fiancée & My Parents

ABSTRACT

An economical and effective design of plates loaded by out-of-plane loads such as pressure or blast can be obtained by using stiffeners instead of increasing plate thickness. Therefore, stiffened steel plates are widely used in many different industries for different purposes and structures. For marine structures, for instance ships, stiffened steel plate walls are used as ship skeleton for resisting wind, hydrostatic and dynamic pressures. In aerospace engineering, these systems are used to resist especially wind pressure. Similarly, such steel wall systems are also widely used in petrochemical industry especially in offshore and onshore platforms as blast walls and blast resistant steel structures as control rooms, office buildings, and living quarters in areas with a high risk of explosion, fire, or danger from toxic materials in petrochemical industry.

For such steel wall structures ultimate strength capacity, wall stiffness, and requirement for weld connection between the wall plate and stiffeners depends on effective breadth of plate, which is the part or breadth of plate working with each stiffener as its flange. This breadth width is typically predicted based on plate nonlinear stress distribution occurring due to out-of-plane loading such as pressure, blast, wind etc. Although there are a number of studies for such cold formed plate systems, they are mainly focused on effective width concept, which is based on in-plane loading only. In other words, there is a need for research to generate engineering design guidelines for predicting effective breadth width for stiffened steel plates subjected to out-of-plane loads.

In the first part of this study, nonlinear finite element models of stiffened plate structures subjected to uniform out-of-plane pressure loading was generated by using

general purpose finite element program Abaqus CAE. The effective breadth of these wall systems was calculated using nonlinear stress distribution through plate thickness and along plate width to determine axial load carried by plate. The effective breadth width was calculated as the plate width needed to carry the same axial load but with a uniform stress, which is equal to the maximum computed stress from the model, along the plate width as defined in the literature. A parametric study was also conducted to determine effects of walls design parameters such as spacing of stiffeners, plate thickness and type of stiffener. For this purpose, a wide range of plate thickness from 30 mm to 10 mm was studied. Similarly, for stiffener angle, flat, boxed and tee sections were also considered. Additionally, seven different spacing ranging 150 cm to 75 cm for the stiffeners were included in the parametric study.

In the second part, effective breadth of the walls was investigated by using simple beam method. In this method, such structures were modeled as a simple beam because modelling and analyzing of these walls require a lot of computational time, high-performance computer, costly finite element software package as well as expert engineering judgment. For this purpose, three prototype walls for different cases; plate yields first, flange yields first, both yield at the same time, were created. At the same time, the walls that have the same geometric and material properties were modeled as simple beams. The correlation between walls and simple beams were discussed by using support reaction per stiffener versus vertical displacement curve. In summary, this part investigates how close the behavior of different featuring walls can be modeled by simple beam method.

ÖZETÇE

Basınç veya patlama yükleri gibi düzlem dışı yüklemeler altında kullanılan çelik plakaların ekonomik ve efektif tasarımı plaka kalınlığını arttırmak yerine takviye elemanları kullanılarak yapılabilmektedir. Bu yüzden, takviyeli çelik plaka yapıları sıklıkla farklı endüstri alanlarında çeşitli amaçlarla kullanılmaktadır. Deniz yapıları için, gemi iskeletlerinde kullanılarak rüzgâr, hidrostatik ve dinamik basınca karşı çalışması sağlanır. Havacılık ve uzay mühendisliğinde özellikle rüzgâr basıncına karşı bu yapılar inşa edilmektedir. Benzer şekilde, bu tip yapılar yangın, patlama ve zehirli madde tehlikesinin yüksek şekilde bulunduğu petrokimya sanayilerinde kullanılan kıyı ve açık deniz platformlarının yönetim odalarında, ofis binalarında ve yaşam alanlarında, patlama duvarı ve patlamaya dayanıklı yapılar olarak kullanılmaktadır.

Takviyeli çelik plaka yapılarında en yüksek dayanım, rijitlik ve duvar ile takviye elemanı arasında gerekli kaynak bağlantısı, plakanın efektif genişliğine bağlıdır. Bu genişlik plakanın takviye elemanı ile birlikte üst başlık gibi çalışan kısmı ya da uzunluğudur. Plakaların efektif genişliği, basınç, rüzgâr ve patlama gibi düzlem dışı yüklemeler altında plakada oluşan doğrusal olmayan gerilmelere bağlı olarak hesaplanır. Her ne kadar efektif genişlik alanında soğuk biçimlenmiş çelik sistemler için birçok çalışma bulunsa da bunlar genel olarak düzlem içi yüklemelere odaklanan çalışmalardır. Diğer bir deyişle, düzlem dışı yüklemeler altında takviyeli çelik plaka yapılarının efektif genişliğini hesaplamak için tasarım esaslarını oluşturacak çalışmalara ihtiyaç duyulmaktadır.

Çalışmanın ilk kısmında, takviyeli çelik plaka yapılarının doğrusal olmayan çoklu elemanlar modelleri, genel amaçlı sonlu eleman programı Abaqus CAE ile yapılmıştır.

Plaka tarafından taşınan eksenel yükü belirlemek için hesaplanan efektif genişlik, plaka genişliği ve kalınlığı boyunca düzlem dışı basınç sonucu oluşan gerilmelere bağlı olarak hesaplanmıştır. Literatür de tanımlandığı şekilde, plakaların efektif genişliği aynı eksenel kuvveti taşıyacak, fakat oluşan maksimum doğrusal olmayan gerilme dağılımına denk gelen, hesaplanmış tekdüze olan gerilme dağılımının genişliği olarak belirlenmiştir. Yapının tasarım parametrelerini oluşturan plaka kalınlığı, takviye elemanları arası genişliği ve profil tipi, parametrik çalışma ile incelenerek efektif genişlik üzerine olan etkisi incelenmiştir. Bu amaçla; 150 cm'den 75 cm'ye kadar olan takviye elemanlar arası genişlik, 30 mm'den 10 mm'ye kadar değişen plaka kalınlıkları ve 4 farklı takviye elemanı tipi parametrik olarak incelenmiştir.

Tezin ikincisi kısmında, yapıların etkin genişliği basit kiriş modellemesi kullanılarak değerlendirilmiştir. Bu metotta, yapılar basit bir kiriş olarak modellenmeye çalışılmıştır, çünkü bu tip yapıların birçok kez modellenmesi ve analiz edilmesi çok fazla işlem zamanı, yüksek maliyetli sonlu elemanlar paketleri ve uzman mühendislik talep etmektedir. Bu amaçla, üç prototip yapı modellenmiştir. Bu yapılar sırasıyla; ilk plakada akma, ilk takviye elemanında akma ve takviye elemanı ile plakanın aynı anda aktığı üç durumu ayrı ayrı ele almaktadır. Aynı zamanda, tamamen aynı geometrik ve malzeme özelliklere sahip basit kirişler oluşturularak onların da analizi gerçekleştirilmiştir. Takviyeli çelik plaka yapıları ve basit kiriş modellerinin birbirleri ile olan ilişkileri mesnet reaksiyon tepkisi-yatay yer değiştirme eğrilerinin kıyaslanmasıyla sonucu belirlenmiştir. Özet ile, bu kısımda yapıların basit kiriş olarak modellenmesinin ne kadar doğru sonuç verdiği test edilmiştir.

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TABLE OF CONTENTS

ABSTRACT vi

ÖZETÇE viii

ACKNOWLEDGMENT x

TABLE OF CONTENTS xii

LIST OF TABLES xiv

LIST OF FIGURES xv

I. INTRODUCTION 1
1.1 Literature Review 6
1.2 Goals and Objectives 11
1.3 Organization of Thesis 12

II. FINITE ELEMENT MODELLING OF SIFFENED STEEL PLATE STRUCTURES & COMPUTATION OF EFFECTIVE BREADTH 13
2.1 Modelling of Prototype Stiffened Plates 14
2.1.1 Analysis Type and Details 20
2.1.2 Material Model used for Prototype Walls 20
2.2 Calculation of Effective Breadth Width 21
2.3 Plate and Stiffener Damage Definition 24

III. PARAMETRIC STUDY ON EFFECTIVE BREADTH OF STIFFENED STEEL PLATE STRUCTURES 26
3.1 Effect of Stiffener Spacing on Effective Breadth 27
3.2 Effect of Plate Thickness on Effective Breadth 32
3.3 Effect of Stiffener Types on Effective Breadth 38
3.4 Effect of Mesh Size on Effective Breadth Width 44

IV. DETERMINATION AND VERIFICATION OF EFFECTIVE BREADTH BASED ON SIMPLE BEAM ANALYSIS 47
4.1 Prototype Stiffened Plates and Simple Beams 48
4.2 Effective Breadth Using Full and Idealized Beam Models 50

V. SUMMARY, CONCLUSION AND FUTURE WORK 58
5.1 Summary 58
5.2 Conclusions 59
5.3 Future Work 62

BIBLIOGRAPHY 64

VITA 66

LIST OF TABLES

Table 1: Steel material properties 21
Table 2: Response limit criteria for components 24
Table 3: Summary of values for parameters 27
Table 4: Geometric properties of plate and stiffener for spacing models 27
Table 5: Geometric properties of plate and stiffener for thickness models 32
Table 6: Geometric properties of plate and stiffener 38
Table 7: Geometric properties of stiffened plate for mesh sensitivity 45
Table 8: Summary of wall sections.. 48
Table 9: Summary of computed effective breadth using different formulae 51

LIST OF FIGURES

Figure 1: Utilization area of stiffened plate structures; (a) Ship, and (b) Offshore platform blast wall [1] [2] 1
Figure 2: Nonlinear stress distribution along plate width [5] 2
Figure 3: Effective width method proposed by von Karman [3]; a-) Real nonlinear stress distribution, b-) Equivalent stress block proposed by von Karman 3
Figure 4: Type of loadings; (a) In-plane pressure, (b) Out-of-plane pressure for effective width and breadth 4
Figure 5: Effective Width Comparison of Eurocode 9, 1.2 Cold-Formed (CF) Structures Part 1.4 [11] 8
Figure 6: Change of effective breadth versus length to breadth ratio for the path of A, B and C [5] 10
Figure 7: Correlation of stress versus stiffener height [19] 11
Figure 8: Typical stiffened plate system 13
Figure 9: (a) Typical stiffened plate and (b) Cross section view with loading and boundary condition 15
Figure 10: Abaqus finite element model of the prototype stiffened plate 15
Figure 11: Roller boundary condition definition for plate ends through coupling 16
Figure 12: Symmetry boundary condition 17
Figure 13: Plate and stiffener mesh 18
Figure 14: Stiffener local mesh 18
Figure 15: Visual representation of S4R shell element and its integration points [20] 19
Figure 16: Plate loading with uniform static pressure 19
Figure 17: Stress distribution in plate; (a) Actual stress condition, (b) Equivalent line load 21
Figure 18: Visual representation of slope for wall; a-) Typical post-stiffener systems; b-) B-B cross-section view 25
Figure 19: Total support reaction force versus mid-span vertical displacement 28
Figure 20: Support reaction force per stiffener versus mid-span vertical displacement 28
Figure 21: Effective breadth width versus slope of stiffener 29

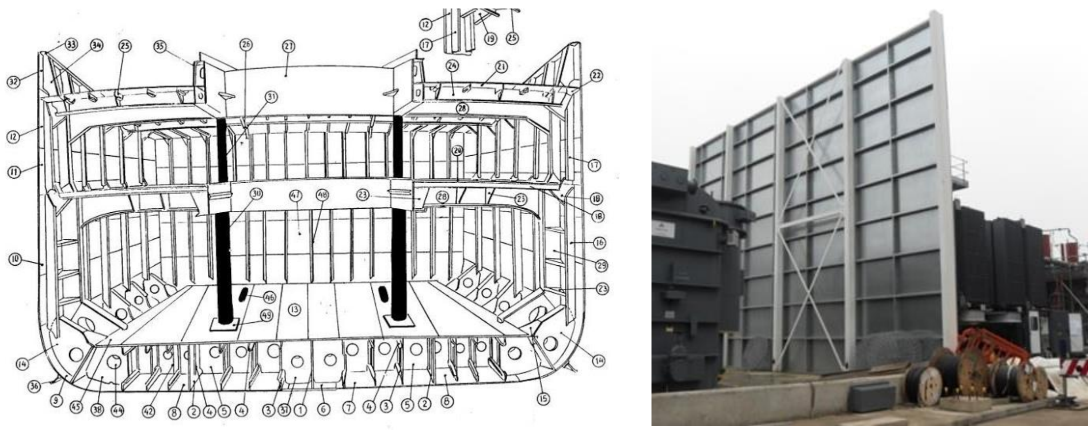
Figure 22: Comparison of computed effective breadth width with Winter and Bruhn expressions for stiffeners spacing of 150 cm 31
Figure 23: Comparison of computed effective breadth width with Winter and Bruhn expressions for stiffeners spacing of 125 cm 31
Figure 24: Total support reaction versus mid-span vertical deflection.......................... 33
Figure 25: Local plate buckling at the mid-span of plate due to compression bending (Scaled to 1.5) 33
Figure 26: Change of effective breadth with plate thickness and stiffener slope 34
Figure 27: Comparison of computed breadth values with expressions proposed by Winter [7] and Bruhn [10] 35
Figure 28: Longitudinal stress distribution for thin plates at plate top and bottom surfaces 36
Figure 29: Average longitudinal stress distribution through thin-plates thickness........ 37
Figure 30: Longitudinal stress distribution for thick plates at plate top and bottom surfaces 37
Figure 31: Average longitudinal stress distribution through thick plates thickness 38
Figure 32: Cross-section view of stiffeners; (a) Tee; (b) Angle; (c) Flat; (d) Boxed 39
Figure 33: Total reaction force versus mid-span vertical deflection for stiffener spacing of 150 cm 40
Figure 34: Total reaction force versus mid-span vertical deflection for stiffener spacing of 100 cm 41
Figure 35: The change of effective breadth for different stiffener sections with spacing of 150 cm 42
Figure 36: The change of effective breadth for different stiffener sections with spacing of 100 cm 43
Figure 37: Average longitudinal stress through plate thickness for 150 cm spacing 44
Figure 38: Reaction force versus displacement at mid-span of plate for different mesh sizes... 45
Figure 39: Effective breadth computed for different mesh sizes 46
Figure 40: (a) Stiffened plate (b) FE model of plate and idealized beam...................... 49
Figure 41: Support reaction versus vertical deflection at midspan for stiffened plate and idealized beam with different breadth width for Wall-A... 52

Figure 42: Support reaction versus vertical deflection at midspan for stiffened plate and idealized beam with different breadth width for Wall-B 53
Figure 43: Support reaction versus vertical deflection at midspan for stiffened plate and idealized beam with different breadth width for Wall-C 53
Figure 44: Wall-A; a) Plate Misses stress contours, b) Longitudinal stress at plastic deformations along plate thickness 56
Figure 45: Wall-B; a) Plate Misses stress contours, b) Longitudinal stress at plastic deformations along plate thickness 56
Figure 46: Wall-C; a) Plate Misses stress contours, b) Longitudinal stress at plastic deformations along plate thickness 57

CHAPTER I

INTRODUCTION

Stiffened plate structures are widely used as a structural wall in a wide range of industrial applications. Basically, these walls are comprised of steel plate and stiffener welded to steel plate with a specific spacing. In aerospace engineering, airplanes incorporate such wall structures to resist strong air current and wind pressures. Similarly, for marine structures such as ships these wall structures are used in modular structures located on shipboard as well as ship skeleton itself to resist hydrostatic and dynamic loads as shown in Figure 1 (a). In petrochemical industry, accidental blast incidents are common in onshore and offshore platforms, therefore, these wall system is used to build blast resistant walls as shown in Figure 1 (b) and structures used as control rooms or shelters to resist blast events. Such wall systems are widely used for critical structures, and building located in critical locations to protect personal and ensure safe operations.



(a) (b)

Figure 1: Utilization area of stiffened plate structures; (a) Ship, and (b) Offshore platform blast wall [1] [2]

Behavior of these stiffened plate depends on how effective the plate work with the stiffeners. In other words, the effective breadth width of plate is the main parameter that controls stiffness and strength of the stiffened wall. Under in-plane or out-of-plane loading, the distribution of stress along the plate between the stiffeners is not uniform due to transmission of shear from stiffeners to the plate. The axial stress in plate diminishes the distance from the web or stiffener increases. In Figure 2, this nonlinear stress distribution is illustrated on a stiffened wall, where σ_{xx} is the stress, *b* is the plate length, and *s* is the spacing of stiffeners. This nonlinear stress distribution was first observed by Galambos [3], and it is known as "*shear lag effect*" [4] in the literature.

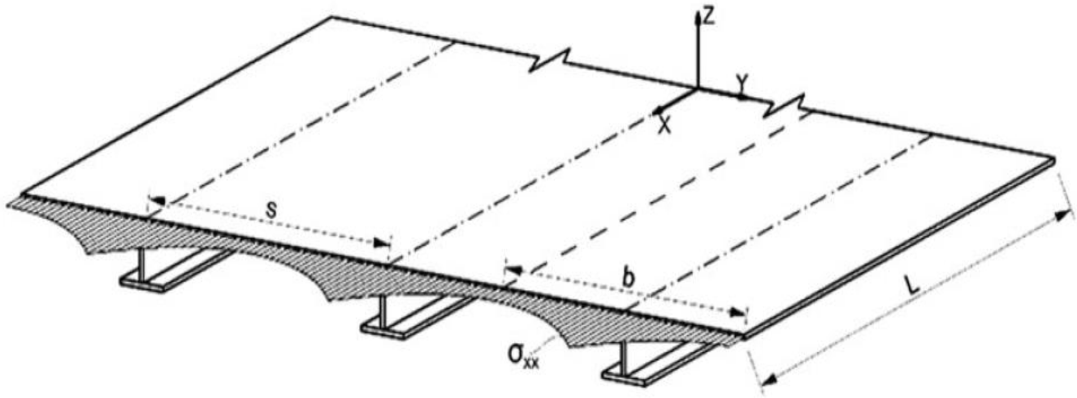


Figure 2: Nonlinear stress distribution along plate width [5]

Stiffened plate structures are typically designed using effective breadth width or effective width concept, which enables designer to estimate behavior (i.e., stiffness, yield, and loading capacity) of the structure by use of simple beam theory. First, von Karman [6] studied effective width concept for cold formed stiffened plates by proposing equivalent stress block. According to this method, actual stress area in plate is converted to an equivalent area with uniform pressure, which is equal to the maximum actual pressure, as shown in Figure 3 (a) and (b) by using (Eq. 1.1)

$$b_{eff} = \frac{\int_{-b/2}^{b/2} \sigma(x)\, dx}{\sigma_{max}} \quad (1.\ 1)$$

Where b_{eff} is effective breadth width or effective width, is $\sigma(x)$ is net axial stress along plate width, and σ_{max} is maximum stress. The change of stress through plate thickness is neglected because plate is considered to be thin since the equation was developed for cold form members under axial loading. Winter [7] [8] [9], Bruhn [10], Euler [11] and many other researchers studied this concept numerically and experimentally to propose different effective width formulas.

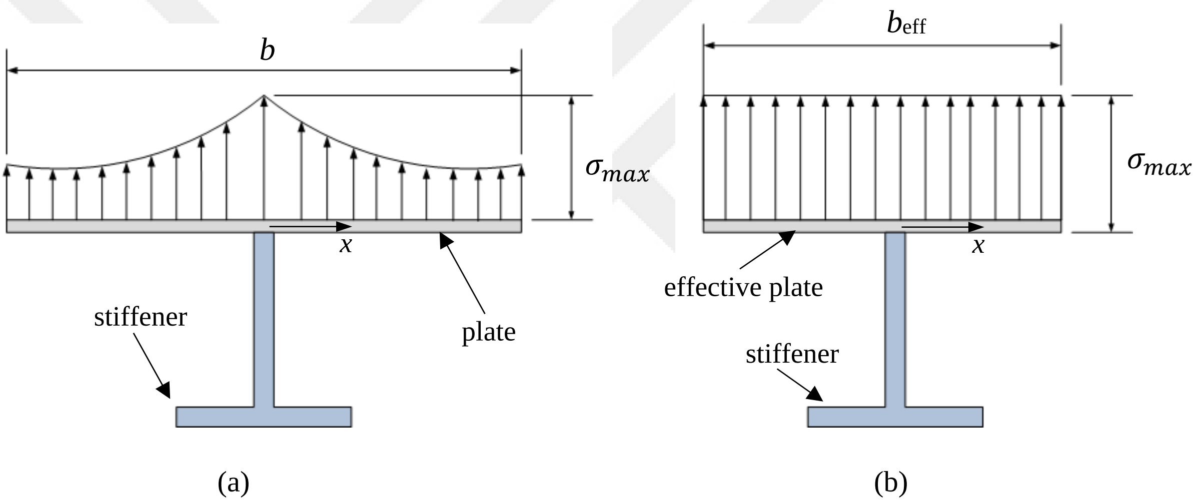
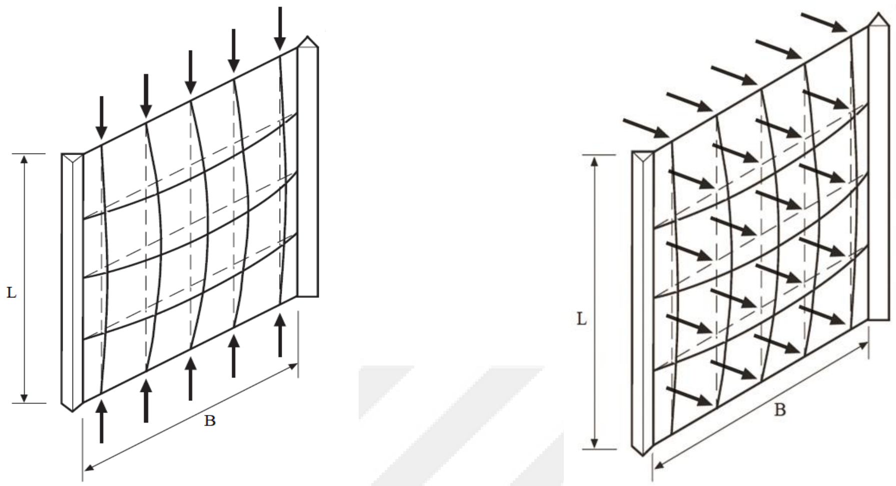


Figure 3: Effective width method proposed by von Karman [3]; a-) Real nonlinear stress distribution, b-) Equivalent stress block proposed by von Karman

However, effective width and effective breadth are the two separate concepts for the stiffened steel plates. This difference was first explicitly stated by Schade [12]. Effective width of such stiffened plates is calculated based on nonlinear stress distribution occurred due to in-plane loads (i.e., axial load) as shown in Figure 4 (a), and proposed equations are mainly based on studies done on cold form stiffened plates to predict their post-buckling strength. On the other hand, effective breadth is the effective plate width for stiffened plates under bending or out-of-plane loads such as pressure loading as shown in Figure 4 (b).



(a) (b)

Figure 4: Type of loadings; (a) In-plane pressure, (b) Out-of-plane pressure for effective width and breadth

Several formulas exist for effective width, and most of them are based on experimental results. However, these formulas are developed to predict mostly post buckling strength of cold form stiffened plates, where the stiffened plate structure is built out of thin plates. Studies focusing on effective breadth width are very limited, and therefore, typically the formulas for effective width are used to predict effective breadth width for design purposes.

To study effective breadth of stiffened structural plates, 3D finite element analysis method was used. Structural analysis of stiffened plates is more complex than available simple closed form equations mainly due to plate bending between stiffeners and along the stiffeners, complex shear transfer between the stiffener and plate, and nonlinear behavior of material. For this purpose, general purpose finite element (FE) software Abaqus CAE [13] was selected since it provides wide range of contact, interaction and material properties, at the same time, it allows to solve linear/nonlinear 3D problems under both static and dynamic loadings accurately within a short computational time. To calculate effective breadth of plates, well-known and widely used in industrial applications definition of breadth width as proposed by Schade [12] was used. The FE results were used to obtain axial stress distribution due to bending through plate thickness and along the plate width. Then, the stress profile was integrated through plate thickness to obtain axial stress distribution along the plate width between the stiffeners.

Because stiffened steel plate structures are used for different applications and loading conditions, a parametric study was conducted to determine effects of plate thickness, type of stiffener and spacing of stiffener. Additionally, finite element analysis is very sensitive to mesh size of model parts, therefore, the sensitivity analysis of mesh size on total reaction forces and effective breadth for stiffened structures models was conducted to obtain proper mesh size.

The main reason using the effective breadth width concept is to enable the designer to evaluate and design stiffened plate structures using simple beam equations. Therefore, analysis of stiffened plates studied using 3D FE models was also done using simple beam approach for different plate breadth width values. The results for support reaction, initial stiffness, and yielding were compared to those obtained from 3D FE models of the entire plate to further evaluate accuracy of computed breadth width and simple beam approach for stiffened plates.

1.1 Literature Review

Stiffened steel plate structures are widely used in offshore and onshore oil and gas production facilities as blast wall and blast resistant steel structures, and in naval and aerospace engineering applications. Therefore, there have been numerous studies to understand behavior of stiffened steel plate structures especially under different load and boundary conditions as well as residual stress and initial imperfections.

Effective width concept was first introduced in 1932 by von Karman et al. [6], who theoretically studied the concept to understand compression behavior of steel plates and proposed first expression for effective width as;

$$\frac{b_e}{b} = \sqrt{\frac{\sigma_{cr}}{\sigma_Y}} \tag{1. 2}$$

where b is full plate width between stiffeners or supports, b_e is effective width, σ_{cr} is critical buckling stress, and σ_Y is yield stress. However, the proposed expression didn't include effects of residual stress and initial imperfections.

Fischel [14] conducted both experimental and computational studies on stiffened steel plates under compression in 1940. It was concluded that induced moment, inter-rivet buckling, and elastic modulus of stiffener and plate had a critical impact on effective width.

Winter [9] justified von Karman formula in 1947 and added geometric nonlinearities and effects of residual stresses into the updated expression, given as;

$$b_e = 1.9t\sqrt{\frac{E}{\sigma_e}}\left(1.0 - 0.574\frac{t}{b}\sqrt{\frac{E}{\sigma_e}}\right) \qquad (1.3)$$

where E is modulus of elasticity and σ_e is edge stress in plate. Winter [7] updated his existing formula in 1970 with a more realistic one based on some 150 experimental tests carried out at Cornell University. Using a lower bound for the test results the coefficient 0.574 was decreased to 0.475, but in the final version of the expression the constant was updated to 0.415 using average test value rather than lower bound values. The formula given by Winter [7] was also verified by experimental tests reported by Yu [15] and published in 2000. Similar studies were conducted by Bruhn [10] in 1973 on aircraft structures, but he proposed a relatively simple formula based on plate thickness, elastic modulus, and yield stress of steel.

Effective width concept has also been given as design guideline in several design specifications especially for cold-formed structures. For example, upgraded Winter's formula by Pekoz [16] [17] was included in both the 1986 and 1996 edition of the *American Iron and Steel Institution* (AISI) [18] and it is still being used as design guideline in the AISI specification for stiffened steel plates under compression. *Eurocode 9, Cold-Formed (CF) structures Part 1.4* [11] has an effective width calculation procedure as well. The guidelines are based on three researchers' work; Winter, Euler and Von Karman. Linear and non-linear (post-buckling) approaches were used for effective width calculations. Nonlinear theory of post-buckling behavior was compared in the code as shown in Figure 5, and the proposed expressions by Winter (Eq. 1.4), Euler (Eq. 1.5) and von Karman (Eq. 1.6) are also included.

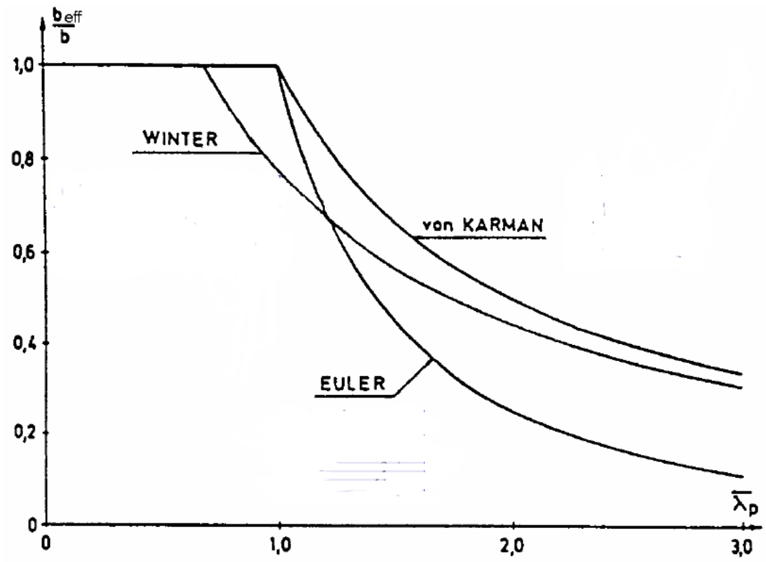


Figure 5: Effective Width Comparison of Eurocode 9, 1.2 Cold-Formed (CF) Structures Part 1.4 [11]

In these expressions, λ_p is given as square root of ratio of material yield stress (f_y) to critical stress (σ_{cr}), b is the spacing between plate edges or distance between stiffeners and b_e is the effective width of plate. In post-buckling approach, nonlinear stress distribution was converted to equivalent rectangular stress block as given in Figure 3.

$$\frac{b_e}{b} = \frac{1}{\lambda_p}\left(1 - \frac{0.22}{\lambda_p}\right) \tag{1. 4}$$

$$\frac{b_e}{b} = \frac{1}{{\lambda_p}^2} \tag{1. 5}$$

$$\frac{b_e}{b} = \frac{1}{\lambda_p} \tag{1. 6}$$

Schade [12] was the first researcher to explicitly distinguish effective width and breath in 1954. Effective width is a concept used for the stiffened plates loaded under in-plane compression loads. On the other hand, when stiffened plate structures loaded with out-of-plane loads such as blast, static pressure, wind etc., then, the part of plate working with the stiffener was defined as effective breadth. Schade carried out a parametric study on stiffened plates, where effects of structural configuration, loading condition, and boundary conditions were investigated to see their impact on the effective breadth. Schade presented a method and design curves based on stress distribution in the plate.

S. Ghelardi [5] et al. performed an extensive research on effective breadth of composite hull stiffened plate structures. Finite element models were used to investigate behavior of the effective breadth of stiffened laminates. Geometric and other typical parameters of composite made ship structures such as width to length ratio, thickness of stiffener and plate, web height as well as boundary condition were taken into account in the parametric study. The effective breadth was calculated using strains instead of stresses due to composite nature of the structure using (Eq. 1.7) where b_{eff} is the effective breadth and ε is the strain. In the end, regression formulae were proposed. Results showed that the type of stiffener has a limited influence on effective breadth. However, thickness of plate has the largest impact on this length because of shear stresses, and web and faceplate thickness have negligible effects on effective breadth width. Figure 6 shows the change in effective breadth width with respect to ratio of span to stiffener spacing. Path A is located on the edge of plate support, Path B is located on ¼ from plate support end, and Path C is located at the mid span of plate span. The difference in reported effective breadth width are most likely due to the fact that plate is subjected to different stress levels due to moment distribution along plate span.

$$b_{eff} = \frac{\int_0^b \varepsilon_{xx}\,(y)\,dy}{\max(\varepsilon_{xx})} \tag{1. 7}$$

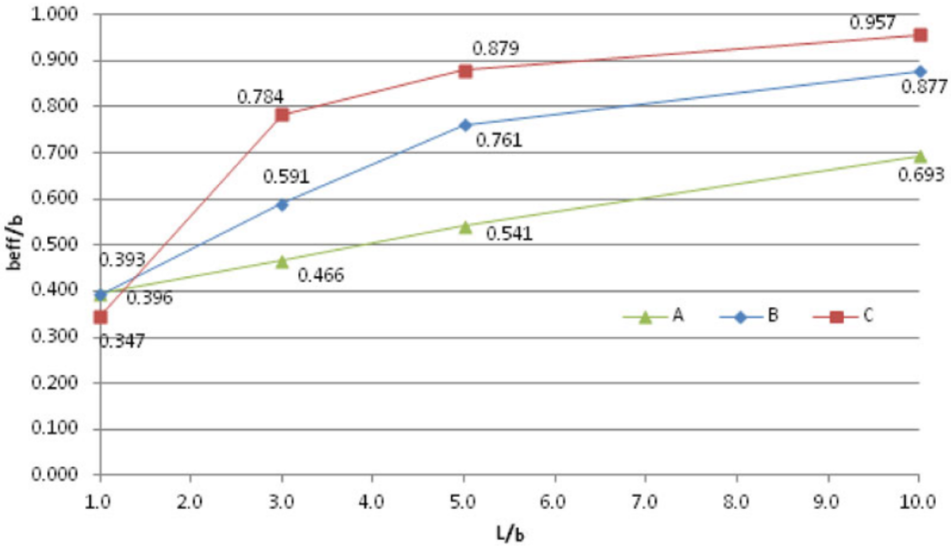


Figure 6: Change of effective breadth versus length to breadth ratio for the path of A, B and C [5]

Yousif M.V. et al. [19] studied on stiffened plate structures to determine the effects of stiffener height on the maximum stress in the plate subjected to pressure load. The plates were square plates clamped rigidly from four sides. In total 160 different models were creased using ANSYS finite element software. A parametric study was performed to investigate effects of plate and stiffener thickness and width and height of stiffeners. As shown in Figure 7, although stiffener height increases, stress generated by out-of-plane pressure tends to be constant for three plate thicknesses considered. Also, it was found that thicker stiffener has a significant effect on the stresses resulted in the plate-stiffener system, than the thinner stiffener.

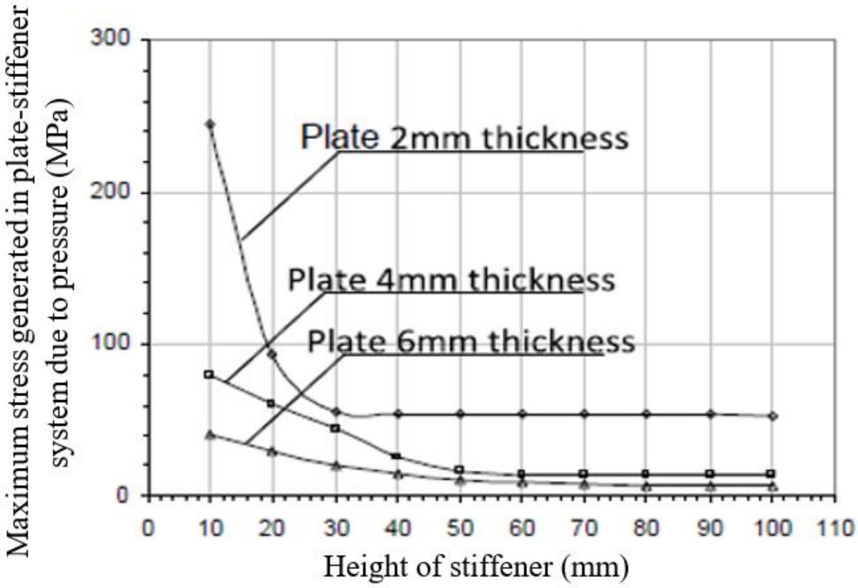


Figure 7: Correlation of stress versus stiffener height [19]

1.2 Goals and Objectives

This thesis aims to expand understanding of effective breadth of stiffened steel plate structures under out-of-plane pressure loadings by studying effects of design parameters on effective breadth width such as plate thickness, type of stiffener as well as spacing of stiffener, and modeling the stiffened steel plate structures as a simple beam to determine corresponding range of effective breadth width. Pursuant to this goal, specific goals and objectives of this study are;

1. Determine the effective breadth for stiffened plate structures under out-of-plane loads by using nonlinear stress distribution through the plate thickness and along the plate between the stiffeners.

2. Determine effects of a large range of parameters such as stiffener type, plate thickness and spacing of stiffeners on breadth width.

3. Determine applicability of existing effective width formulas, which are

widely used for prediction of breadth width in design of stiffened plate structures.

4. Determine validity and accuracy of computed effective breadth width to predict actual behavior of stiffened plate system through simple beam models.

1.3 Organization of Thesis

This report consists of five main chapters. Introduction of stiffened plate structures and effective breadth width, and literature review related are included in “Chapter I”. The details of finite element modelling analysis of selected stiffened plates and methodology used for computing effective breadth width are discussed in “Chapter II”. As a part of parametric study, effects of plate thickness, stiffener spacing, type of stiffener, and mesh size on effective breadth width are investigated “Chapter III”. In “Chapter IV”, modelling and analyzing of stiffened plates is done using simple beam method to determine validity and accuracy of computed effective breadth width through simple beam model to predict actual behavior of stiffened plate structures. At last, summary of study, conclusions and proposed future works are included in “Chapter V”.

CHAPTER II

FINITE ELEMENT MODELLING OF SIFFENED STEEL PLATE STRUCTURES & COMPUTATION OF EFFECTIVE BREADTH

Plate structures are complex engineering elements in terms of design and analysis since 3D stress distribution is much more complex than that assumed by simple closed form equations or design charts. The membrane effects, material and geometric nonlinearities, and biaxial bending further complicate stress state at a given section. Figure 8 shows a typical stiffened plate structure. The presence of stiffeners further complicates the stress distribution in plate due to moment about axis parallel and perpendicular to the stiffeners. In addition, in the vicinity of the stiffeners, the stress state is much more complex due to stiffeners carrying the shear and interaction between the stiffeners and plate.

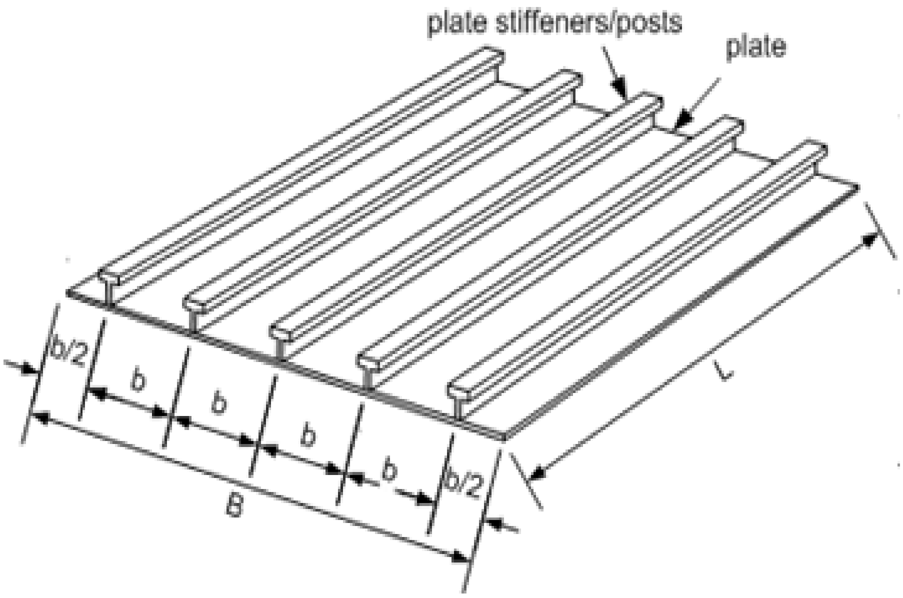


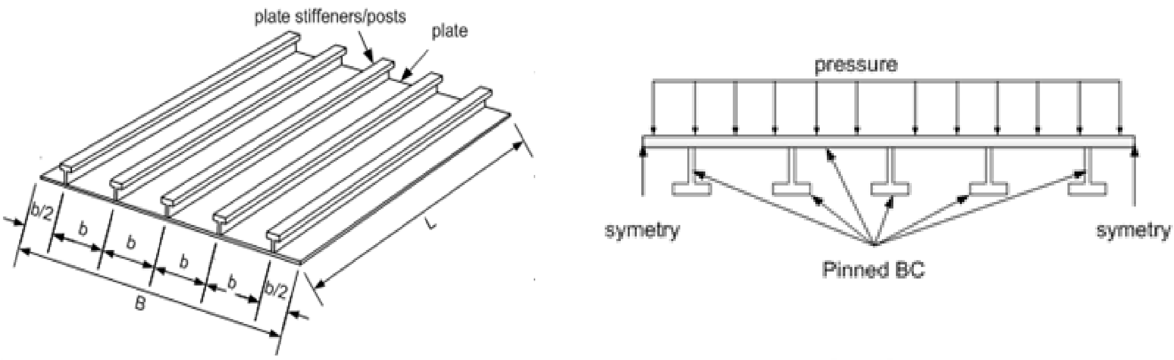
Figure 8: Typical stiffened plate system

Because the definition of plate effective breadth depends on stress distribution through plate thickness and along plate spanning between the stiffeners, finite element (FE) analysis method was selected to accurately capture 3D stress state for the plate and stiffeners both in elastic and plastic ranges. It should be noted that such stiffened plate structures are typically designed to go under large plastic deformations. For example, when such steel stiffened plates are used for blast applications as blast wall or blast resistant buildings, they are designed to experience ductility as high as 12.

Abaqus is one of the pioneering finite element software, commonly used in both academia and industry to model complex engineering problems. In this study, Abaqus 6.14 general purpose finite element program [13] was selected since it is capable of solving complex engineering problems including geometry and material nonlinearities. In addition, it provides a wide range of contact, interaction properties, and material library, which makes Abaqus one of the preferred software for industries including but not limited to aerospace engineering, civil engineering, and marine structures etc.

2.1 Modelling of Prototype Stiffened Plates

A prototype stiffened plate as given Figure 8 was selected to study the effective breadth width. The plate thickness, type and geometry of stiffeners, and stiffener spacing were the main parameters investigated. In FE analysis, solid and shell elements are two common elements used for modelling complex structural systems. However, because thickness of plate is relatively small compared to other dimensions, shell element is selected to model the whole structure. In other words, both plate and stiffeners including stiffeners web and flange were modelled using shell elements. The loading was assumed to be uniform distributed static load (i.e., pressure) and boundary condition was assumed to be roller (i.e., pin) on both ends. It should be noted that the boundary condition is assumed to eliminate membrane effects, which is typically neglected in breadth width definition and further complicate the definition of breadth with.



(a) (b)

Figure 9: (a) Typical stiffened plate and (b) Cross section view with loading and boundary condition

The developed finite element model for the prototype stiffened plate is shown in Figure 10. The mid-span of the plate was partitioned to monitor stresses and deflection of the plate under applied loads. Due to assumed loading and boundary conditions, the mid-span is the location of plastic hinge (i.e., location of maximum moment) and maximum vertical deflection. All reported stresses and deflection were monitored at the mid-span.

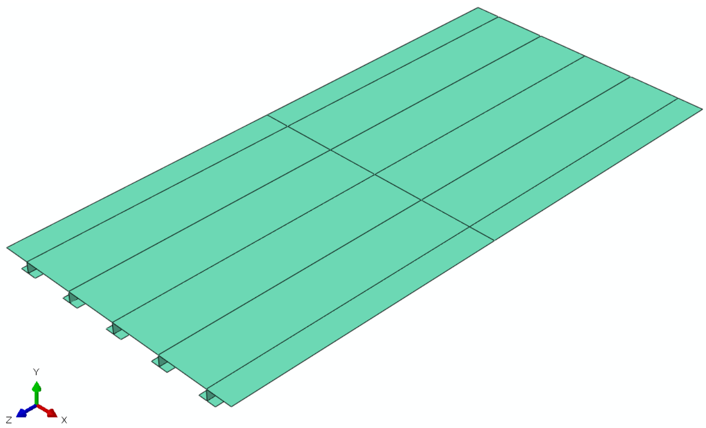
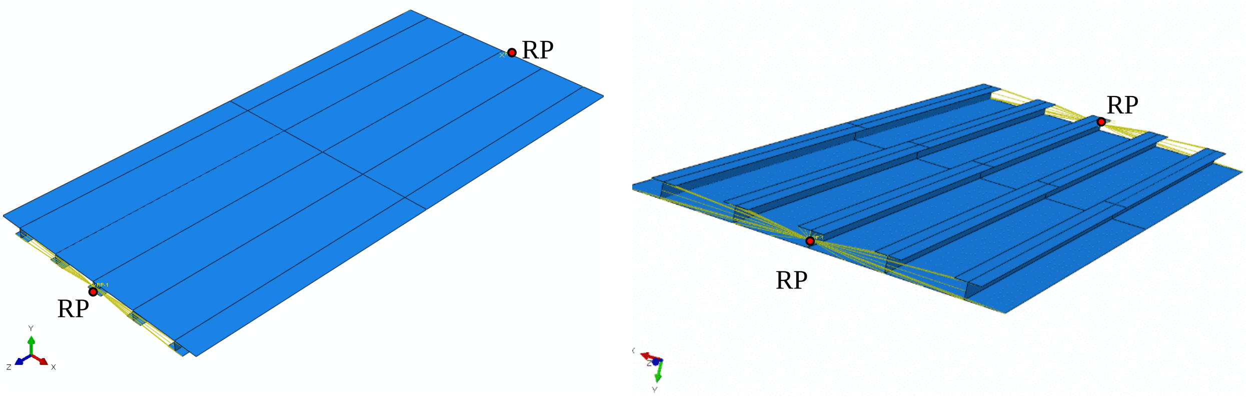


Figure 10: Abaqus finite element model of the prototype stiffened plate

In the developed model, sets of stiffeners were included in the developed models. Although a much simpler model with only one stiffener and plate extending on both sides of the stiffener *b*/2, where *b* is typical spacing of stiffeners, would be sufficient to capture stress state, a much larger model with more stiffeners was selected to ensure that plate stresses are not affected from defined symmetric boundary condition for two plate edges parallel to the stiffeners.

The roller boundary condition for plate ends was applied through coupling constraint. For this purpose, two reference points (RP) were defined at each end, and plate and stiffener end nodes were coupled to these reference points as shown in Figure 11. The boundary condition then was defined for the reference points by constraining RP points displacement in vertical direction only. To ensure stability and successful analysis of the structure, a single node at the mid-span and along center stiffener was further restrained for displacement along the stiffeners. This approach is acceptable since selected node is located at the symmetry line, which is not supposed to have any displacement along stiffener.



(a) Top view (b) Bottom view

Figure 11: Roller boundary condition definition for plate ends through coupling

Additional boundary condition was defined for the two free edges of plate spanning along the stiffeners. The modelled plate was assumed to be a part of much larger stiffened plate structure, therefore, symmetry boundary condition was defined for the two free edges as shown in Figure 12.

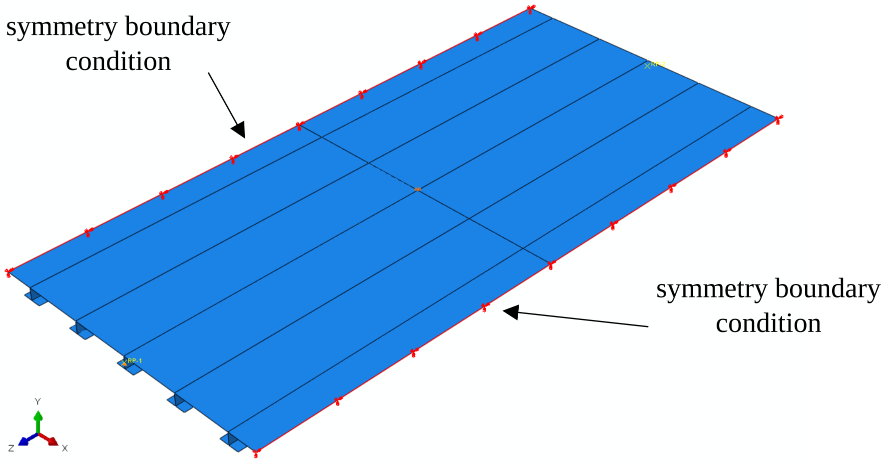


Figure 12: Symmetry boundary condition

For meshing the plate and stiffeners, a nominal mesh size of approximately 60 mm was used as shown in Figure 13. A mesh sensitive analysis was done as given in *Section 3.4*, and this mesh size was found to be reasonable. However, it should be noted that a smaller mesh size was used for the stiffener web locally to ensure that the web is defined at least with five elements as shown in Figure 14. The selected mesh size was found to be suitable to determine stress variation along the plate between the stiffeners.

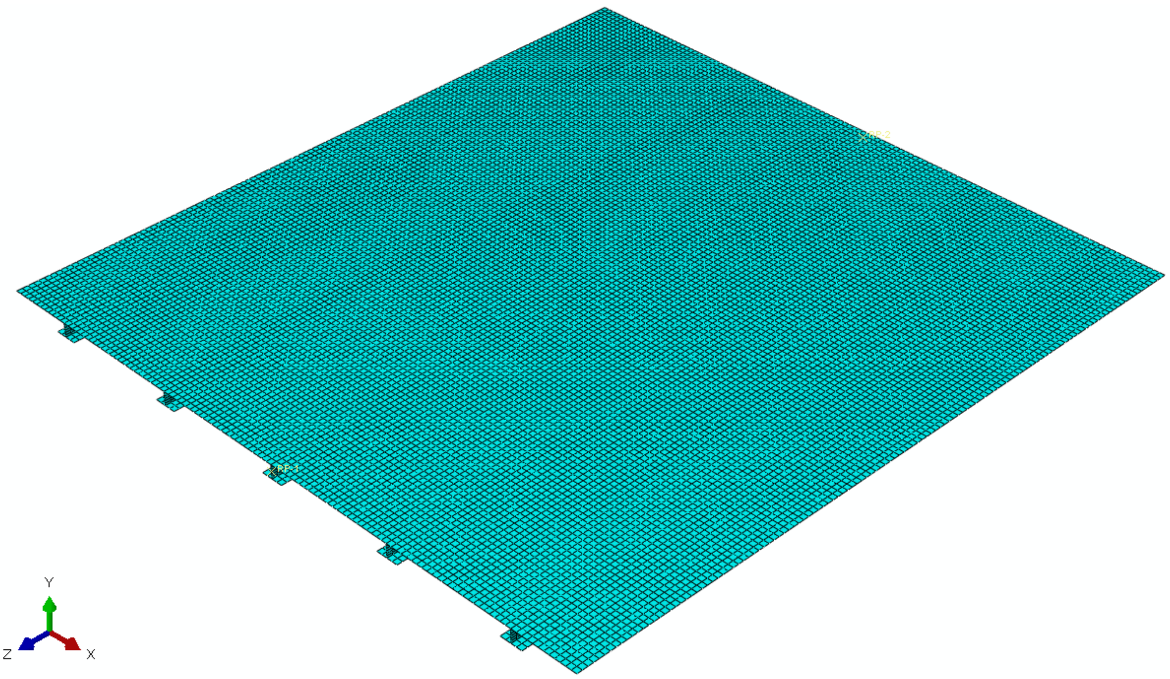


Figure 13: Plate and stiffener mesh

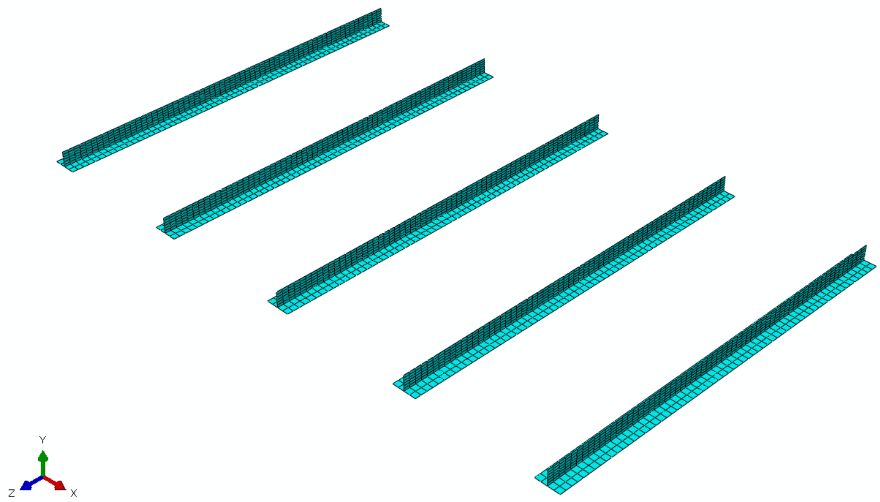


Figure 14: Stiffener local mesh

There are several different shell elements available in Abaqus, where each is designed for specific purposes and applications. In this study, S4R shell element, which is a 4-node general purpose shell element with five integration points through thickness as shown in Figure 15, was used for both plate and stiffeners including the web and flanges. The stresses through plate thickness were monitored plate bottom, mid-plane, and top, which correspond integration points 1,3, and 5, respectively.

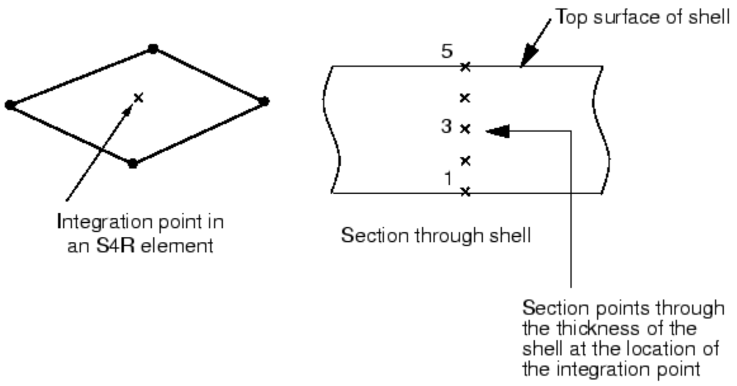


Figure 15: Visual representation of S4R shell element and its integration points [20]

The stiffened plate was loaded with uniform distributed pressure as shown in Figure 16. The uniform pressure loads were applied to stiffened plate incrementally. In addition, such stiffened plate structures are typically designed to resist blast or hydrostatic pressures, therefore, uniform distributed loading was selected instead of some point loading.

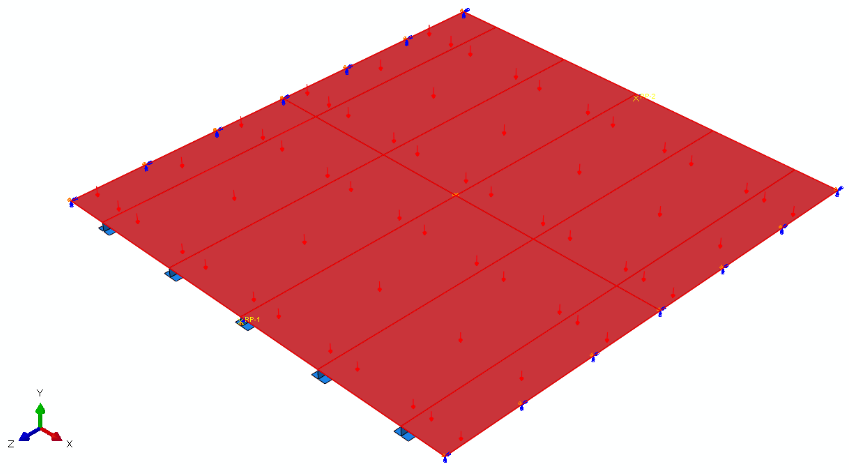


Figure 16: Plate loading with uniform static pressure

2.1.1 Analysis Type and Details

A prototype stiffened plate as given Figure 16, pressure loading was applied with a static standard loading step. In other words, the analysis performed was load controlled. The analysis was performed either until plate structure becomes unstable (typically due to local buckling of plate under compression when plate is relatively thin) or until the desired vertical deflection was obtained. Because the performed analysis was load controlled analysis, a 5% damping in terms of dissipated energy fraction was defined for the analysis. This typically does not affect the analysis results but ensure that model runs when there are small drops in the loading at large deflections. However, in the cases that this damping was not enough to run the models due to local buckling of plate in the vicinity of mid-span, analysis type was changed from static loading to dynamic explicit. However, a quasi-static loading a mass scaling was used with the dynamic explicit analysis step to minimize kinetic energy and to achieve quasi static loading. The quasi-static loading condition was ensured by monitoring kinetic energy and adjusting mass scaling accordingly.

2.1.2 Material Model used for Prototype Walls

For both plate and stiffeners elastic perfectly plastic steel material model was used. The assumed material properties are given in Table 1. In other words, the material properties of steel plate and stiffeners were assumed to be the same (no composite material). The elastic-perfectly plastic material model is commonly used in engineering applications, and conservatively, strain hardening region and increase in strength are neglected. The cases where stiffener and plate steel material grades are different are out of scope of this study. However, it should be noted that difference in plate and stiffener material grades is not expected to affect general conclusion of this study.

Table 1: Steel material properties

Density (kg/m^3)	Elastic Modulus (MPa)	Yield Stress (MPa)	Poisson's Ratio
7850	200000	345	0.3

2.2 Calculation of Effective Breadth Width

The presence of stiffener changes the stress distribution through plate thickness and along the plate spanning between the stiffeners as shown in Figure 17. In the initial definition of effective width as proposed by von Karman [6] and Winter [7], the compressive stress in plate was assumed to be constant through thickness at a given location as given in Figure 2 since the plate was thin cold-formed plate. The effective width was defined as the plate width needed to carry the same load carried by the plate width b but with a uniform compressive stress, which is equal to the maximum compressive stress in actual stress profile.

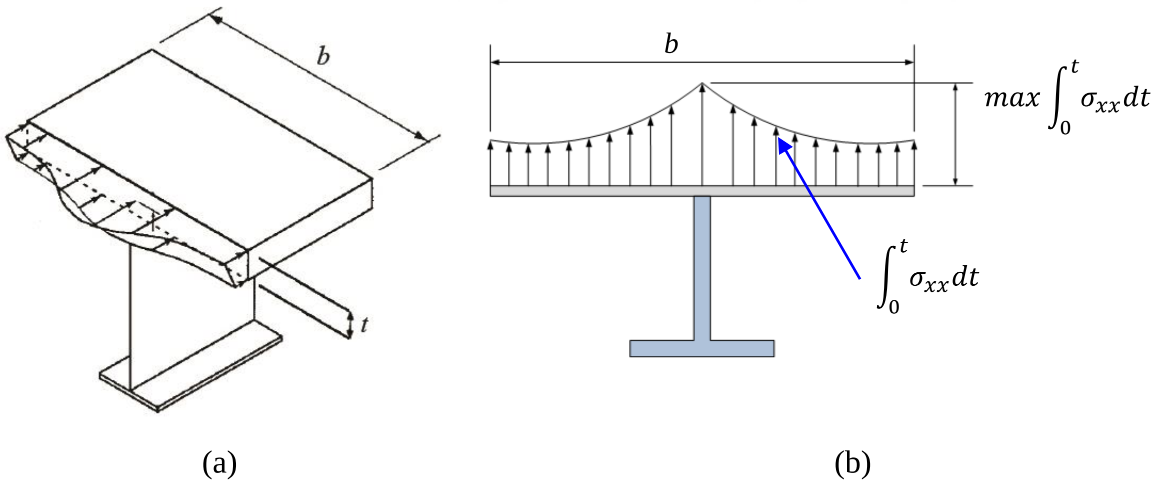


Figure 17: Stress distribution in plate; (a) Actual stress condition, (b) Equivalent line load

However, for plates stiffened with relatively thick structural plates instead of cold-formed thin plates, the actual stress variation through plate thickness is significant and need to be considered in the definition of breadth width or effective width. Figure 17 shows actual variation of stress through plate thickness and along the plate. This stress profile was first converted to a line load simply integrating axial stress σ_{xx} (compression stress) to a line load. The line load profile, which resembles stress profile assumed for initial definition of effective breadth/width, was used to compute effective breadth as shown in Figure 3 and through following equation;

$$b_{eff} = \frac{\int_0^b \int_0^t \sigma_{xx}\, dy\, dx}{\max\left[\int_0^t \sigma_{xx}\, dy\right]} \tag{2. 1}$$

Where b_{eff} is the effective breadth width, t is the plate thickness and σ_{xx} is the stress in plate along stiffener spanning direction. This definition of breadth width calculation is consistent with definition first done by Schade [12].

In performed analysis of stiffened plates the stress in plate at bottom, mid-plane, and top surfaces were recorded along plate width over a path at plate mid-span. The recorded stresses histories were numerically integrated through thickness and along plate using following expressions;

$$\int_0^t \sigma_{xx}\, dy = \frac{(\sigma_{xx})_B + 2(\sigma_{xx})_M + (\sigma_{xx})_T}{4}\, t \tag{2. 2}$$

$$\int_0^b \int_0^t \sigma_{xx}\, dy\, dx = \frac{1}{2} \sum \left(\left(\int_0^t \sigma_{xx}\, dy \right)_{X=Xi} + \left(\int_0^t \sigma_{xx}\, dy \right)_{X=Xi+1} \right) (\Delta x) \tag{2. 3}$$

In addition to the computed effective breadth, the closed form equations initially developed for effective width rather than effective breadth were also used. This includes the expressions proposed by Winter [7] and Bruhn [10] as given in (Eq. 2.4) and (Eq. 2.5), respectively. It should be noted that these expressions are actually proposed for effective width rather than breadth, but they are very commonly used in industry to predict effective breadth. These equations are given as;

$$b_e = 1.9\, t \sqrt{\frac{E}{f_{max}}} \left[1 - 0.415 \left(\frac{t}{b}\right) \sqrt{\frac{E}{f_{max}}}\right] \tag{2. 4}$$

$$b_e = 1.9\, t \sqrt{\frac{E}{f_y}} \tag{2. 5}$$

Where E is elasticity modulus, f_{max} is the maximum stress occurred along the thickness of plate, t is the plate thickness and f_y is the yield stress of the material. In these equations, typically, f_{max} is replaced by yielding stress of the material while designing structures expected to go under plastic deformations such as blast resistant structure. As the equation shows, the formula that Bruhn used is relatively simple comparing to Winter's equation, which includes effects of initial imperfection, residual stresses, and spacing between stiffeners.

2.3 Plate and Stiffener Damage Definition

The effective breadth is sensitive to stress levels and maximum plate deflections. To ensure that results from this study can be compared to other studies or results from plate structures with different span lengths, instead of plate or beam maximum deflection history, the corresponding slope was used. Defining damage using slope and/or ductility is commonly done especially for blast design of structures. In this study, performance evaluation of stiffened plate structures is based on the criteria given in Design of Blast-Resistant Buildings in Petrochemical Facilities [21]. The response limits are specified as low, medium and high. The structural element can have none to slight permanent damage in low response limit. For medium response, some repairable permanent deflection can be seen on structure or its components. When structure is on or above the high response limit, it is not expected to fail, but permanent and irreparable damage is expected.

Response limit criteria of hot rolled steel compact secondary members (beams, girts, purlins) given in the specification was used to evaluate performance of stiffeners. As seen in Table 2, the response limits of stiffeners for different damage levels according to that specification are presented. Although this criterion given in the table are for the structures under dynamic loading such as blast, these limits can also be used as a reference to examine performance of stiffened plate structures.

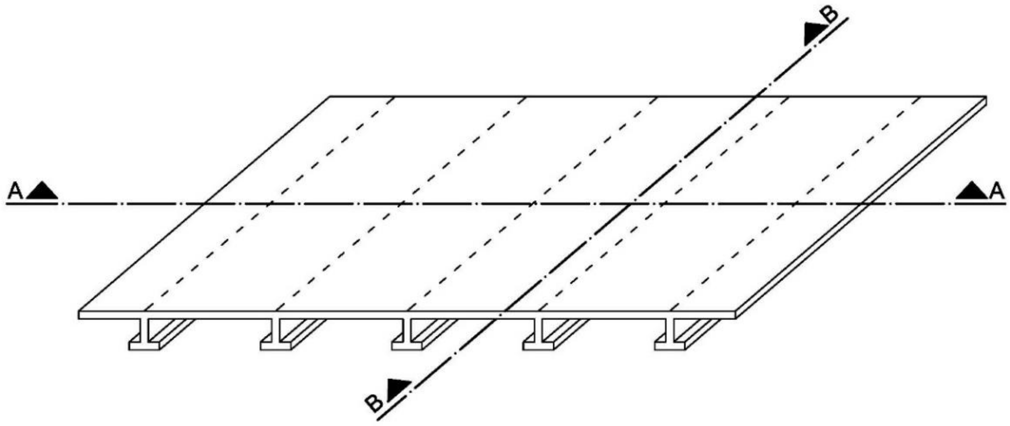
Table 2: Response limit criteria for components

Component	Low Response		Medium Response		High Response	
Criteria	μ_{max}	Θ_{max}	μ_{max}	Θ_{max}	μ_{max}	Θ_{max}
Stiffener	3	2	10	6	20	12

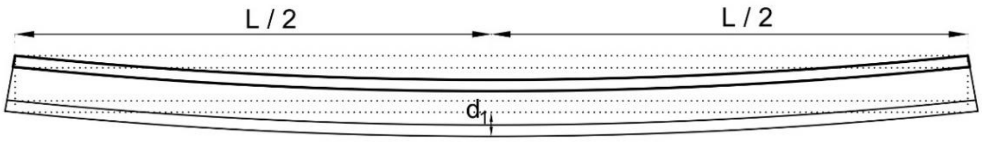
Slope values of stiffened plate structures were calculated based on (Eq. 2.6). As seen in Figure 18 (b), slope of stiffener depends on the maximum vertical deflection of the mid-point and span length.

For stiffeners and plate supported by the stiffeners, the rotation is;

$$\theta_1 = \tan^{-1}\left(\frac{d_1}{\frac{L}{2}}\right) \tag{2. 6}$$



(a)



(b)

Figure 18: Visual representation of slope for wall; a-) Typical post-stiffener systems; b-) B-B cross-section view

CHAPTER III

PARAMETRIC STUDY ON EFFECTIVE BREADTH OF STIFFENED STEEL PLATE STRUCTURES

Stiffened steel plate structures are widely used in aerospace engineering, petrochemical industry as for instance blast resistant buildings and blast resistant walls. While designing such structures, it is very important to properly predict or calculate effective breadth width since the capacity of the wall and its design are based on effective plate breadth. Typically, the expression used to predict effective breadth are those developed to predict effective width but not breadth. For example, von Karman [6], Winter [7] and Bruhn [10] expression are all developed for effective width and they are used for effective breadth, too. Therefore, a parametric study is performed in this section to determine sensitivity of effective breadth width for several design parameters including plate thickness, type of stiffener, and spacing of stiffeners. The most commonly used types of stiffeners (e.g., tee, angle) and a wide range of stiffener spacing were chosen to determine their effects on effective breadth. Additionally, thickness of the plate significantly effects the structure load carrying capacity, yielding, and initial stiffness. Therefore, a wide range of available plate thickness was selected and analyzed as well. A summary of values for the selected parameters are given in Table 3.

Table 3: Summary of values for parameters

Plate Thickness (mm)									
29	25	22	21	20	18	16	14	13	11
Spacing, *b* (cm)									
150		140	125	115		100	90	75	
Type of Stiffener									
Tee			Angle		Flat		Boxed		

3.1 Effect of Stiffener Spacing on Effective Breadth

Stiffener spacing is one of the most critical parameters for design of stiffened plates since it effects load carrying capacity and stiffness of system, consequently, effective breadth width for the plate. To understand its effects on the capacity and effective breadth width, stiffener spacing was increased from approximately 75 cm up to 150 cm. For stiffeners, tee-section was selected. A summary of section geometry, and thickness values for each part is given in Table 4.

Table 4: Geometric properties of plate and stiffener for spacing models

Type of Stiffener	Width, *B* (cm)	Length, *L* (cm)	Plate Thickness (mm)	Web Thickness (mm)	Flange Thickness (mm)	Web Length (cm)	Flange Width (cm)
Tee	760	800	12.5	11.5	20	16	25

When the number of stiffeners increases due to decreasing stiffener spacing, the force at which the stiffened plate yields increases as shown in Figure 19. However, the reaction force per stiffener as shown in Figure 20 are not much different. The main reason for this is the fact that effective breadth for the sections is calculated to be approximately 60 cm at large deflections as given in Figure 21, and this computed, which is less than the minimum stiffener spacing of 75 cm.

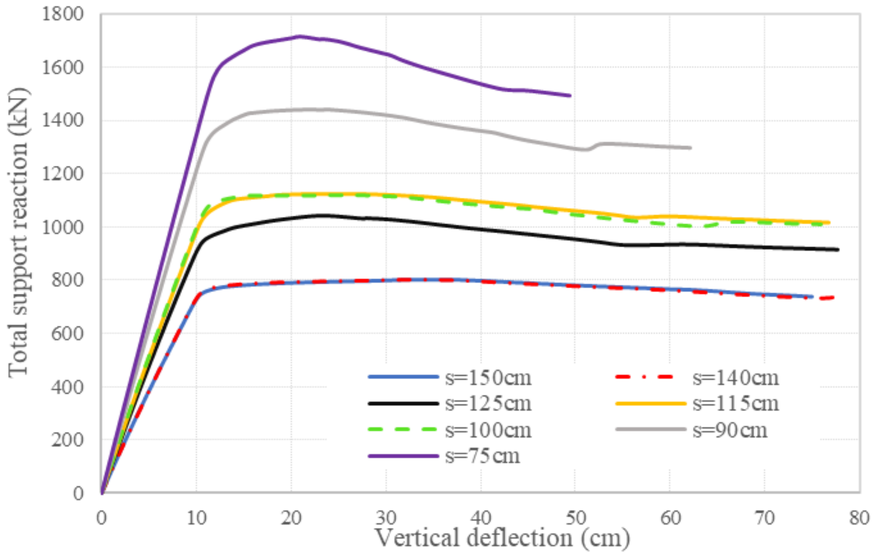


Figure 19: Total support reaction force versus mid-span vertical displacement

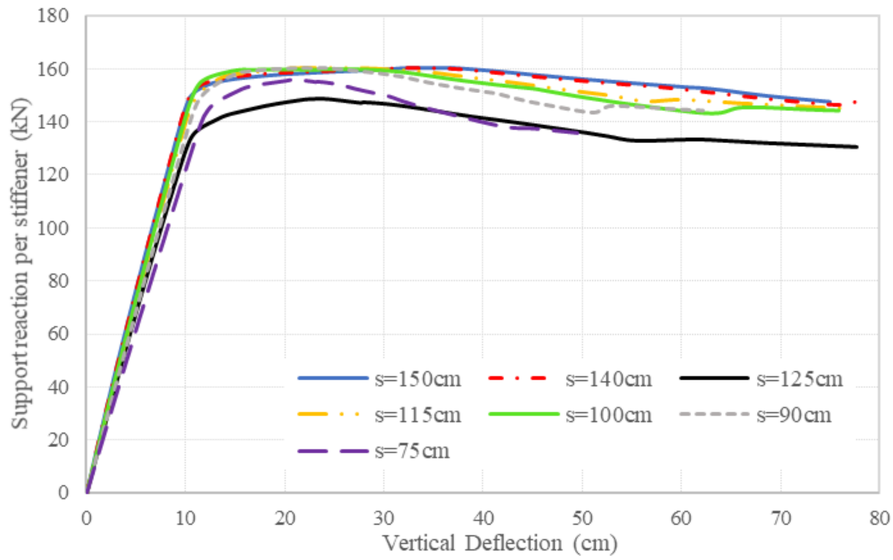


Figure 20: Support reaction force per stiffener versus mid-span vertical displacement

Figure 21 shows computed effective breadth for each stiffener spacing considered. The effective breadth values were computed at a number of plate deflection (i.e., stress level), which is reported as slope for the x-axis. The slope was simply computed as slope of line connecting plate roller support to the point of maximum deflection on stiffener, which occurs at mid-span. The yielding started to occur at top surface of plate just above stiffener at a slope of approximately 0.4°. The results show that at elastic range or at small deflections (small plate stress levels) for the stiffened plate configuration, the effective breadth is equal to approximately to spacing of the stiffeners. However, conservatively, 80-90% of spacing can be assumed as the effective breadth. However, as the deflection (slope) and plate maximum stress increases, the effective breadth decreased rapidly. At about 4° slope, the effective breadth decreased to approximately to the same value of 60 cm for all stiffener spacing. The results show that for stiffener spacing larger than the minimum effective breadth, which occurs at plastic range, the effect of stiffener spacing is negligible for plastic range. However, in elastic range effective breadth may be assumed to be equal to 80-90% of stiffener spacing.

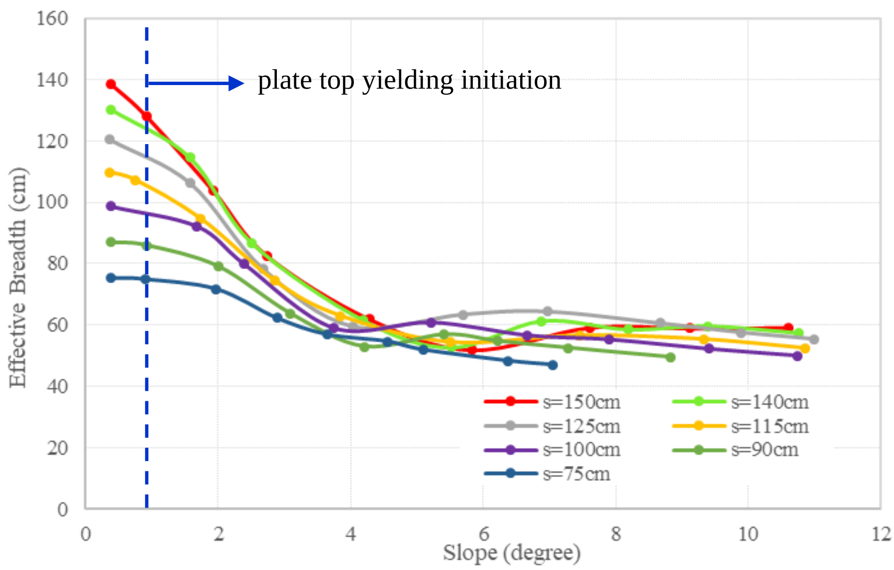


Figure 21: Effective breadth width versus slope of stiffener

The computed effective breadth values were also compared to expression proposed by Winter [7] and Bruhn [10]. To compare the expression with computed values, 150 cm and 125 cm spacing were selected. The expression proposed by Bruhn is only a function of plate thickness, modulus of elasticity, and yield stress so independent of stiffener spacing. In other words, the expression does not include any variable that depends on stiffener spacing. However, the expression proposed by Winter include effect of stiffeners spacing. In addition, the equation is based on maximum stress in plate. The maximum stress f_{max} in plate was computed using following expression;

$$f_{max} = max\left[\int_0^t \sigma_{xx}\, dy\right] \tag{3. 1}$$

Figure 22 and Figure 23 shows comparison of computed effective breadth to those computed using Winter and Bruhn expressions for stiffener spacing of 150 cm and 125 cm, respectively. The expression proposed by Bruhn is only valid for plastic range, and it is a constant value. The results show that both Bruhn and Winter expressions predict similar effective breadth values and they are in good agreement with the values computed in this study in the plastic range. However, in the elastic and transition regions, the computed values of breadth in this study are slightly larger than those predicted using Winter expression. Although Winter expression was developed for cold-formed stiffened plates and consider buckling of plate, the expression seems to be reasonable to predict effective breadth. One potential reason for Winter formula predicting smaller breadth width is very likely the fact that expression was developed mainly considering plate post buckling behavior.

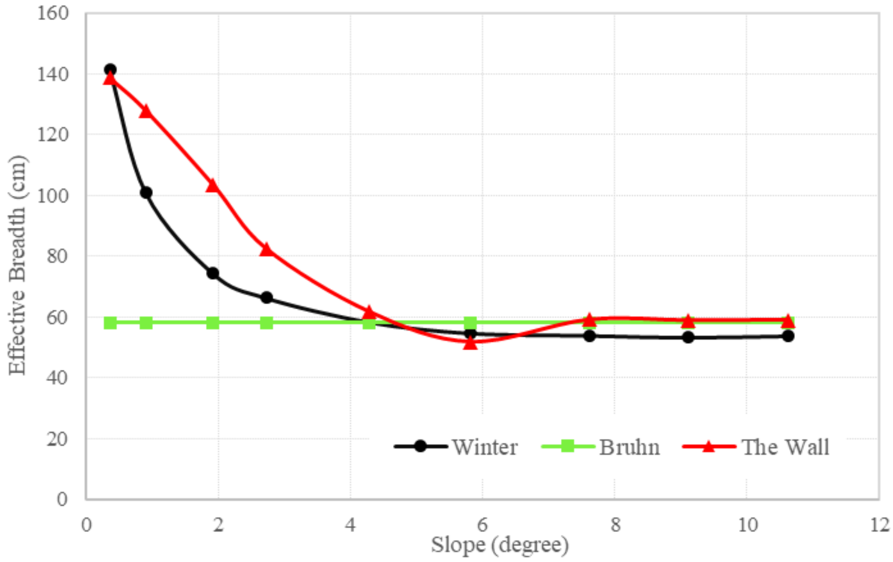


Figure 22: Comparison of computed effective breadth width with Winter and Bruhn expressions for stiffeners spacing of 150 cm

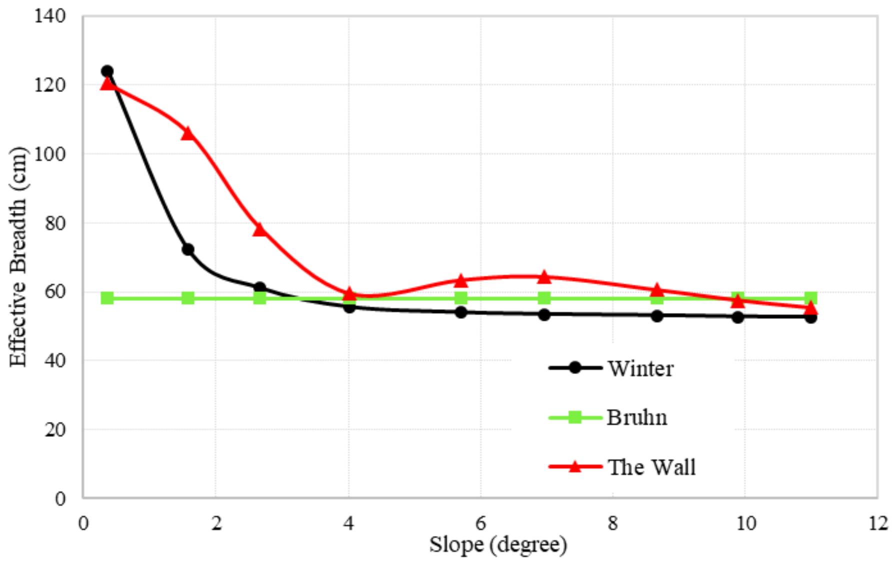


Figure 23: Comparison of computed effective breadth width with Winter and Bruhn expressions for stiffeners spacing of 125 cm

3.2 Effect of Plate Thickness on Effective Breadth

Plate thickness is one of the main design parameters since it significantly affects the performance of the stiffened wall. In addition, the plate thickness is probably the main design parameter affecting the material cost. For the parametric study, a tee section was selected as stiffener with a spacing of 150 cm. The properties of the section are given in Table 5. For plate thickness, total 10 plate thickness values were selected (i.e., 29, 25, 22, 21, 20, 18, 16, 14, 13, 11 mm) based on their availability and likelihood to be selected for industrial application. The selected plate and tee section dimensions were converted from available steel sections in imperial units to metric units.

Table 5: Geometric properties of plate and stiffener for thickness models

Type of Stiffener	Width, *B* (cm)	Length, *L* (cm)	Spacing (cm)	Web Thickness (mm)	Flange Thickness (mm)	Web Height (cm)	Flange Width (cm)
Tee	760	800	150	11.5	20	16	25

Figure 24 shows total support reaction versus plate mid-span deflection for each selected plate thickness. The results show that change in plate thickness affects the initial elastic stiffness of the stiffened plate and post yielding stiffness. Both stiffness values increase with plate thickness. In addition, the yielding force also increases, as expected, with increasing plate thickness. However, the plate mid-span deflections at which yielding occurs are not very sensitive to plate thickness. In addition, it should be noted that force versus deflection curves also show that stiffened plate with plate thicknesses 11 mm and 13 mm had some drop in carried load at plastic deflections due to local plate buckling happening at the mid-span due to bending compression stress in plate as seen in Figure 25.

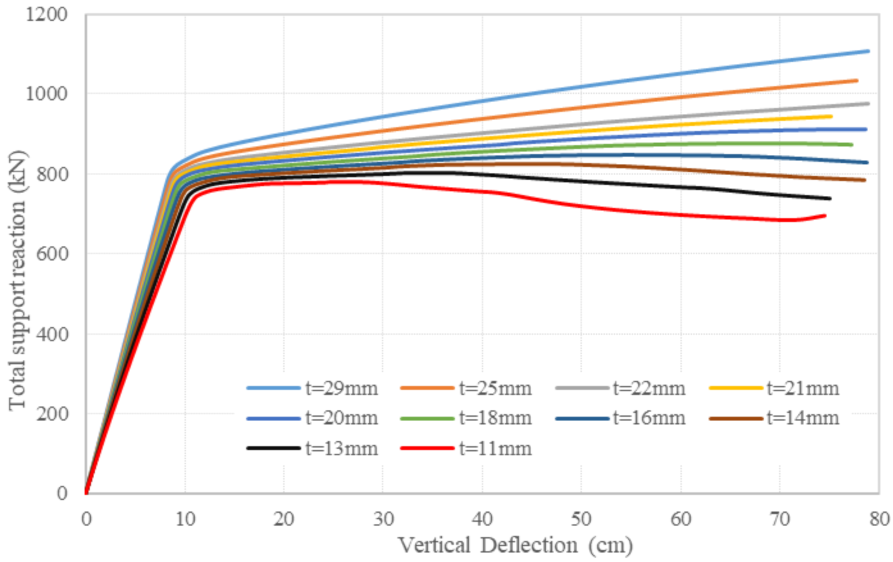


Figure 24: Total support reaction versus mid-span vertical deflection

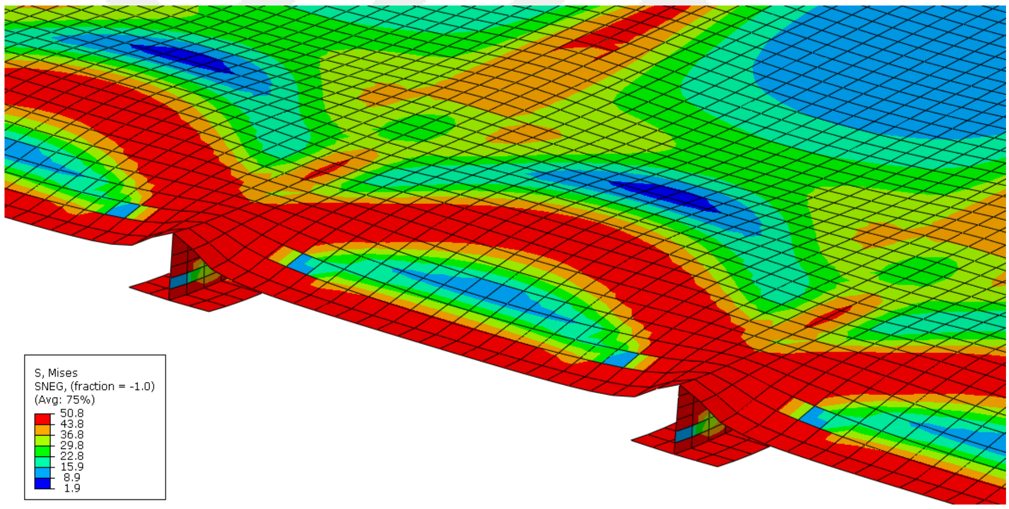


Figure 25: Local plate buckling at the mid-span of plate due to compression bending (Scaled to 1.5)

The computed effective breadth values for each plate thickness are given in Figure 26 as a function of stiffener deflection slope. It should be noted that all plates yielded approximately at a deflection of 10 cm, and this corresponds to a slope of 1.4 degrees. The results show that effective breadth value is almost constant and approximately equal to 80-90% of stiffener spacing for elastic deflections for all plate thickness values considered. However, once the plate yields (i.e., slopes larger than 1.4 degrees) the effective breadth is very sensitive to plate thickness. For plates with larger thickness, the effective breadth is also larger. However, after slope of approximately 8 degrees, the effective breadth converged to approximately 50-60 cm as shown in Figure 26. In other words, the effective breadth value is not much sensitive to plate thickness at stress levels relatively smaller than yielding and at deflections corresponding to full section yielding. However, still plate thickness is one of the most important design parameters affecting effective breadth value.

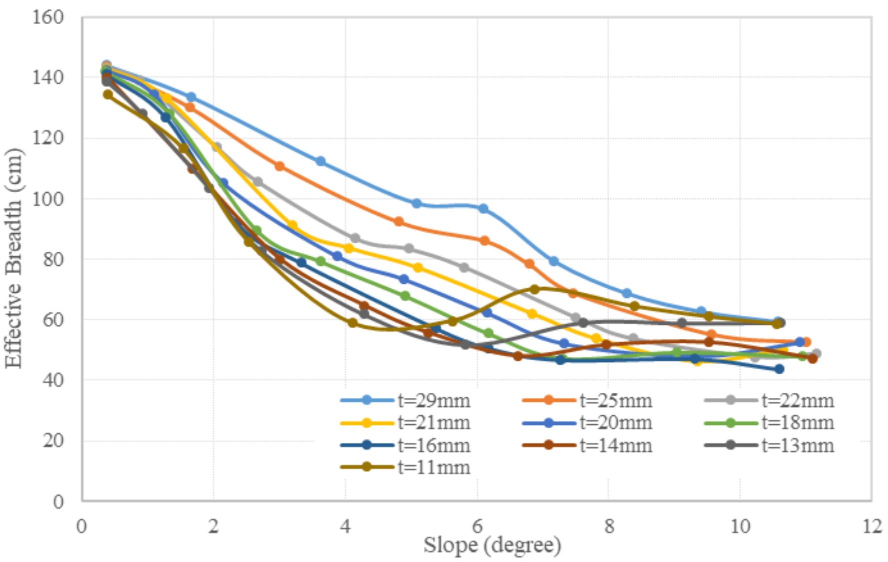


Figure 26: Change of effective breadth with plate thickness and stiffener slope

The computed effective breadth values for each plate thickness at slope values 3.6° and 5.4° were determined and plotted as given in Figure 27. Also, the effective width expression proposed by Winter [7] and Bruhn [10] were included for each plate thickness. Both expressions include plate thickness as a parameter. In addition, for both expression maximum stress in steel plate was taken as plate yielding. The results show that the predictions of Bruhn expression for effective breadth are much larger than those computed and predicted using Winter expression. The result of Winter expression yields between those computed for slope 3.6° and 5.4° as shown. The comparison shows that Winter expression fits to computed values, and it can be used to predict effective breadth. However, it should be noted that for plates with large deflection (plasticity), the computed effective breadth values are smaller than those predicted using Winter and Bruhn expressions. This finding shows that for cases with large plasticity, these two expressions might be unconservative.

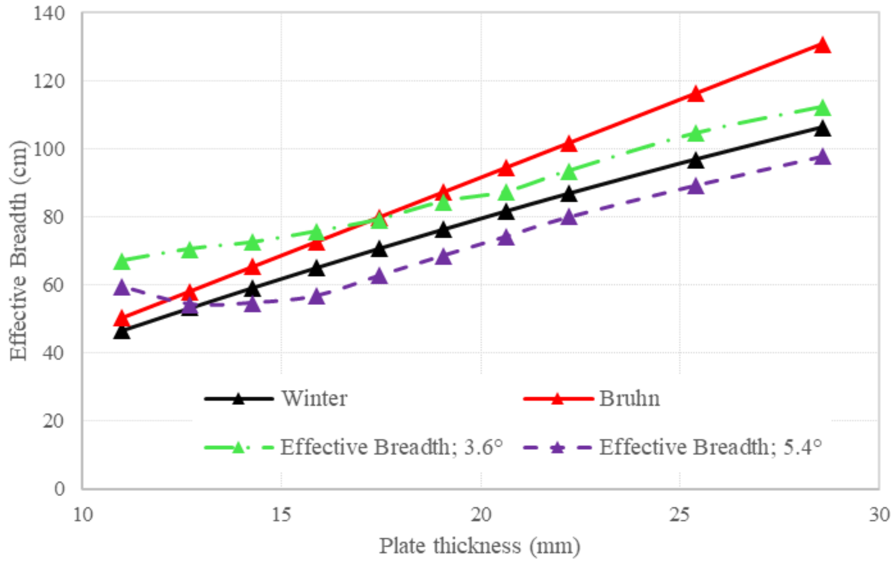


Figure 27: Comparison of computed breadth values with expressions proposed by Winter [7] and Bruhn [10]

Because stress and yielding of plate top and bottom surfaces depend on plate thickness, plates were grouped into categories as thin and thick plates. Plate 11, 13, and 14 mm thick were considered as thin plates and plates thicker than 14 mm were considered as thick. Figure 28 and Figure 29 shows plate stresses in the stiffeners spanning direction on plate top and bottom surfaces as well as average stress through plate thickness for thin plates at plastic range. The results show that presence of stiffener significantly effects stress distribution in plate around the stiffener. This effect is in fact called shear leg effect and its well-known. Figure 30 and Figure 31 show the stress distribution at plastic range for thick plates. The results still show that presence of stiffener affects stress distribution in plate in the vicinity of stiffener. However, as plate thickness increases, the effects of stiffener on plate stress distribution in the vicinity of stiffener is not as significant as that for thin plates.

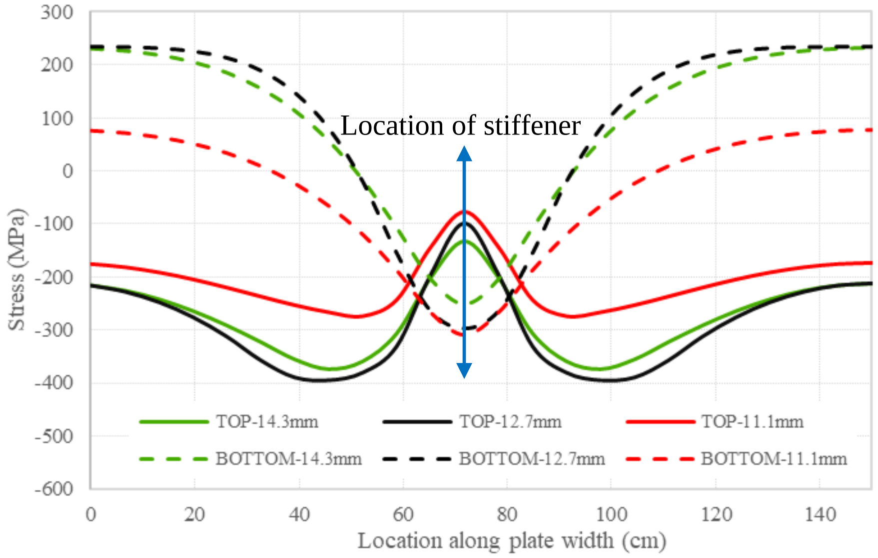


Figure 28: Longitudinal stress distribution for thin plates at plate top and bottom surfaces

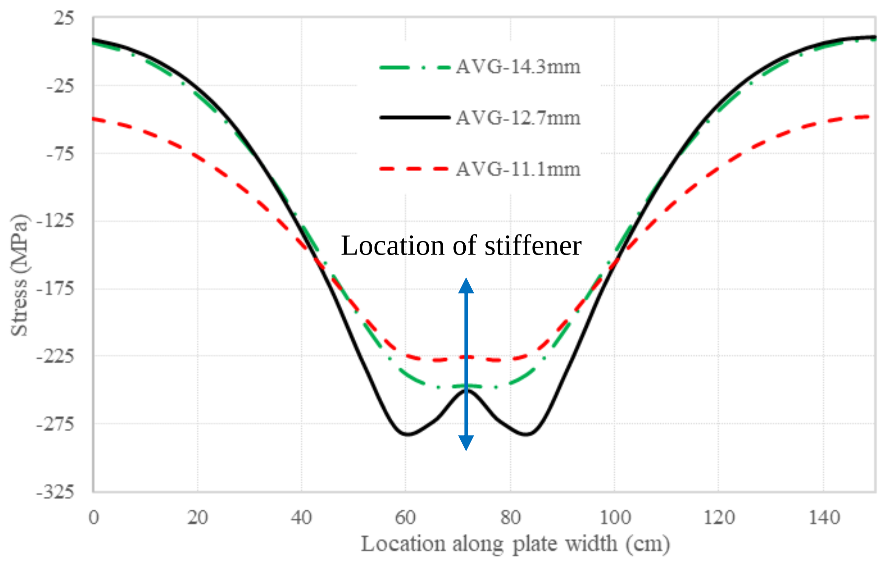


Figure 29: Average longitudinal stress distribution through thin-plates thickness

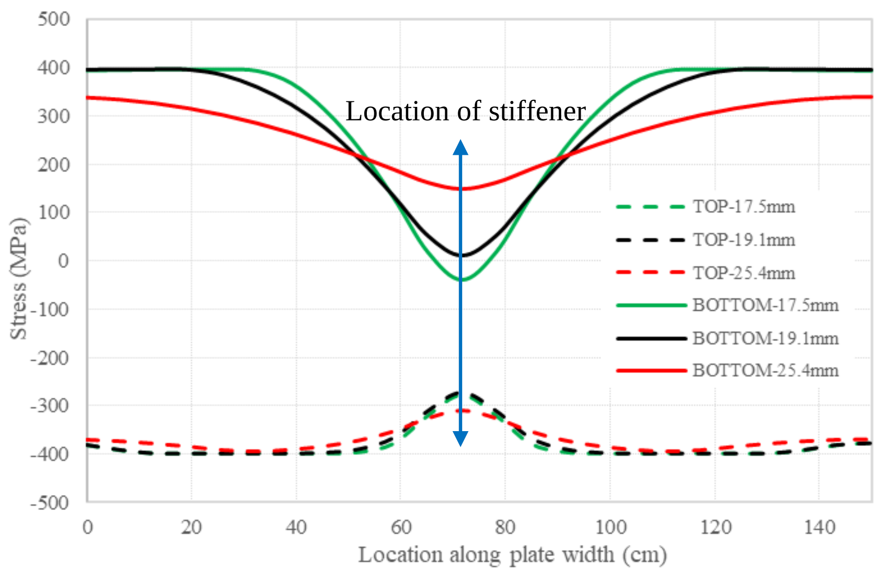


Figure 30: Longitudinal stress distribution for thick plates at plate top and bottom surfaces

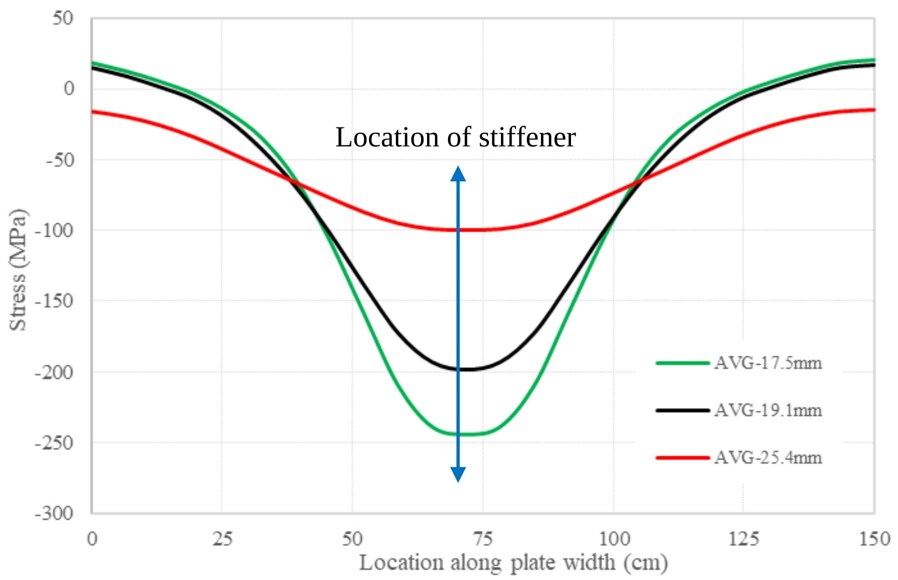


Figure 31: Average longitudinal stress distribution through thick plates thickness

3.3 Effect of Stiffener Types on Effective Breadth

There are several different sections used as stiffener for plates. These stiffeners are typically selected based on criteria such as structural performance, ease of fabrication, and cost. In this section, four different stiffener sections, namely, tee, angle, flat and boxed sections were selected since they are widely used as stiffener. For the spacing of the stiffeners, spacing of 150 cm and 100 cm were considered. A summary of geometric section properties of the stiffeners are given in Table 6, and general view and definition of section parts are given in Figure 32.

Table 6: Geometric properties of plate and stiffener

Stiffener	Width B (cm)	Length L (cm)	Spacing b_e (cm)	Plate Thickness t_p (mm)	Web Thickness t_w (mm)	Flange Thickness t_f (mm)	Web Depth h (cm)	Flange Width b_f (cm)
Tee	760	800	150 & 100	12.5	11.5	20	16	25
Angle						20		25
Flat						-		-
Boxed						20		25

For the stiffeners, flange and web thicknesses as well as web height were kept constant. However, it should be noted that there is no flange for flat stiffener and flange width of angle is only half of tee and boxed section flange. In other words, for the tee and boxed stiffener sections, the only difference is the stiffener section shape and boxed section extra web. Therefore, theoretically, the plate with tee and boxed stiffener sections should have very similar behavior in terms of stiffness and load carrying capacities as well as effective breadth width. The plate with flat stiffener, on the other hand, does not have a flange attached to the stiffener, and therefore, it is expected to yield before all other sections, and therefore have smaller load capacity and stiffness.

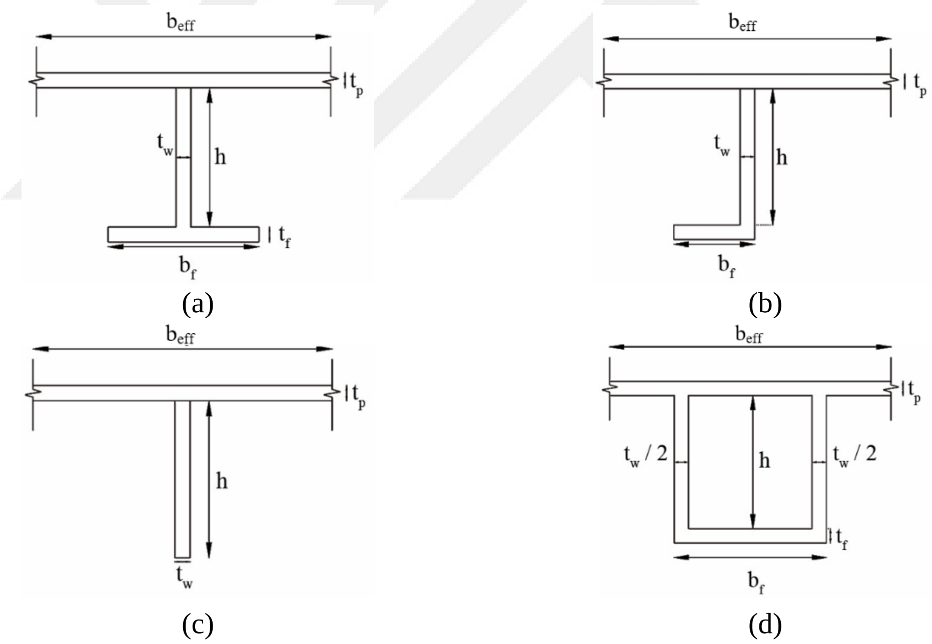


Figure 32: Cross-section view of stiffeners; (a) Tee; (b) Angle; (c) Flat; (d) Boxed

The stiffened plates were loaded with out-of-plane pressure and roller boundary condition was defined for both ends with additional displacement constraint at the plate midpoint for lateral displacement stability as discussed in the modelling section. The total force and plate vertical deflection at the mid-span over the middle stiffener were monitored. The computed total support reaction over one support versus mid-span vertical deflection curves are given in Figure 33 and Figure 34 for stiffener spacing 150 cm and 100 cm respectively. For both spacing values considered, the plate with tee and boxed stiffener sections had similar force versus displacement curves both in terms of stiffness and load capacity since both stiffeners have the same flange geometry (width and thickness). The plates with stiffener having angle and flat (solid rectangular) sections had significantly lower stiffness and load carrying capacity since the stiffener flange area is only half of tee stiffener flange for the angle stiffener, and flat stiffener does not have a flange attached. For stiffener spacing as expected, the decreased spacing of stiffeners caused a significant increase in the load carrying capacity and initial stiffness of the plates. The plate with flat stiffener had the smallest load carrying capacity and initial stiffness for both stiffener spacings due absence of flange. These load versus displacement curves indicate that flat plate should not be preferred as plate stiffeners if they are intended to be used to increase load carrying capacity or initial stiffness of stiffened plate structures.

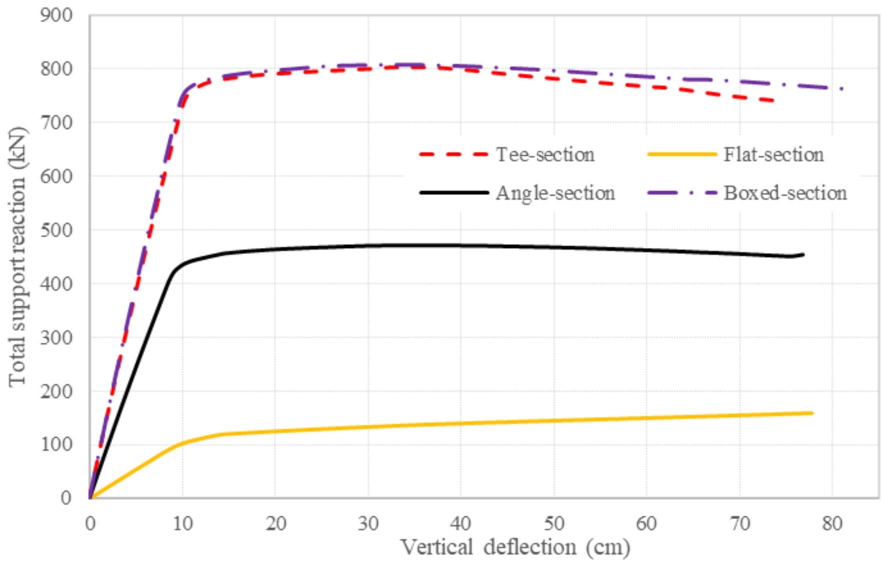


Figure 33: Total reaction force versus mid-span vertical deflection for stiffener spacing of 150 cm

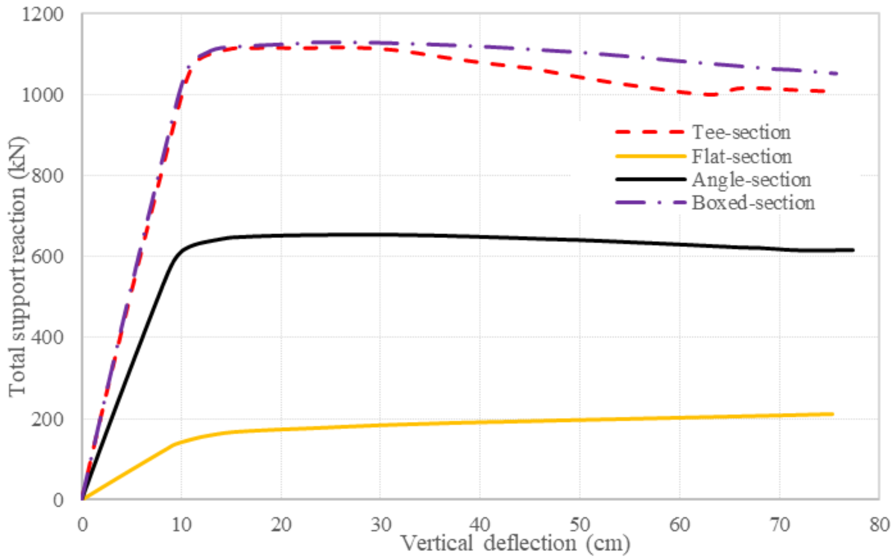


Figure 34: Total reaction force versus mid-span vertical deflection for stiffener spacing of 100 cm

The effective breadth width for the stiffened plates was calculated at different stress and deflection levels using the plate stress at the bottom and top surfaces as well as at the mid height of the plate as discussed in Chapter II. The computed effective breadth values are given in Figure 35 and Figure 36 for stiffener spacing of 150 cm and 100 cm respectively. The results for stiffener spacing of 150 cm show that type of stiffener does not have any practical effects on effective breadth especially for slope values less than 6 degrees (i.e., vertical deflection of approximately 40 cm). However, as plasticity and deflection increase, the effective breadth width values diverged from each other. For the plate with the angle and flat stiffener, the effective breadth remained almost constant while it slightly increased for plate with boxed and tee stiffeners due to stress redistribution at high plasticity. In conclusion, for plate with stiffener located at 150 cm spacing, the effective breadth is not sensitive to type of the stiffener used.

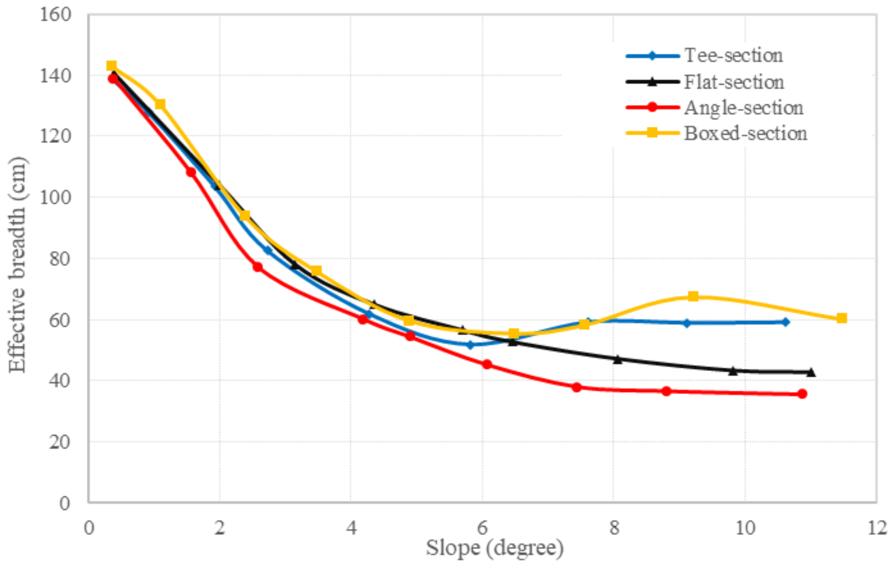


Figure 35: The change of effective breadth for different stiffener sections with spacing of 150 cm

The computed effective breadth width for stiffener spacing of 100 cm are given in Figure 36. The results show similar trends. In other words, the effective breadth values were almost the same for slope up to 4 degrees (i.e., vertical deflection of approximately 28 cm). The only exception was the plate with flat stiffener, for which the effective breadth was much smaller than that computed for other stiffeners at small slopes (deflections). As plasticity and deflection of stiffened plate increased the difference between computed breadth values increased, but the maximum difference between computed values was not more than 20 cm. In summary, the results presented indicate that effective breadth is not much sensitive to type of stiffener especially at small deflections (slope less than 4 degrees). However, the difference can be as much as 20 cm at high plastic levels. In addition, the tee and boxed stiffeners had largest computed effective breadth width, which indicate that they should be preferred over flat and angle stiffeners.

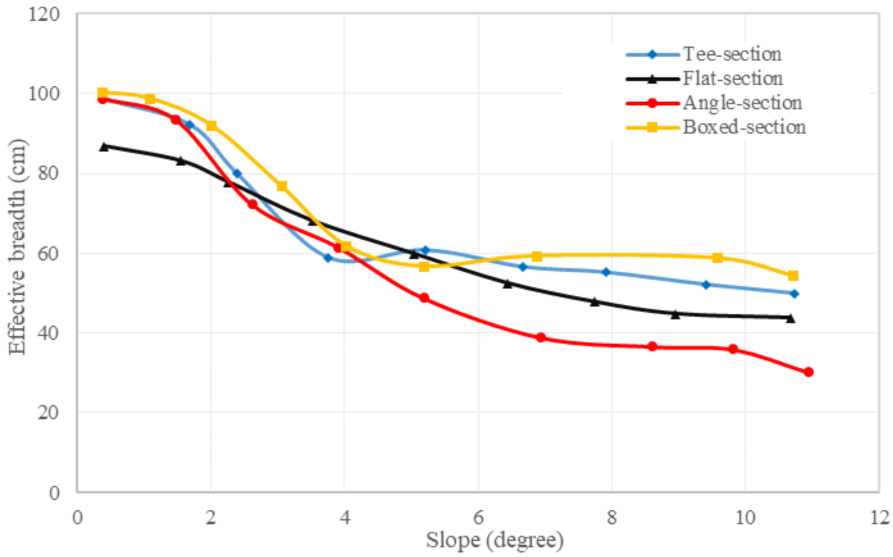


Figure 36: The change of effective breadth for different stiffener sections with spacing of 100 cm

The longitudinal average stress profile through plate thickness, which is used to compute effective breadth, is given in Figure 37 at deflection of 35 cm, where plate is significantly yielded. The results show that stiffener type and section used affects the average stress distribution through plate thickness in the vicinity of the stiffeners. The average stresses for the boxed and tee section are similar as expected. That is because these sections have larger stiffener flanged and consequently larger load carrying (i.e., moment) capacity. As expected, the plate with flat plate as stiffener had the smallest average stress through plate thickness. However, it should be noted that the effective breadth does not only depends on maximum stress but also depends on stress profile due to definition of effective breadth.

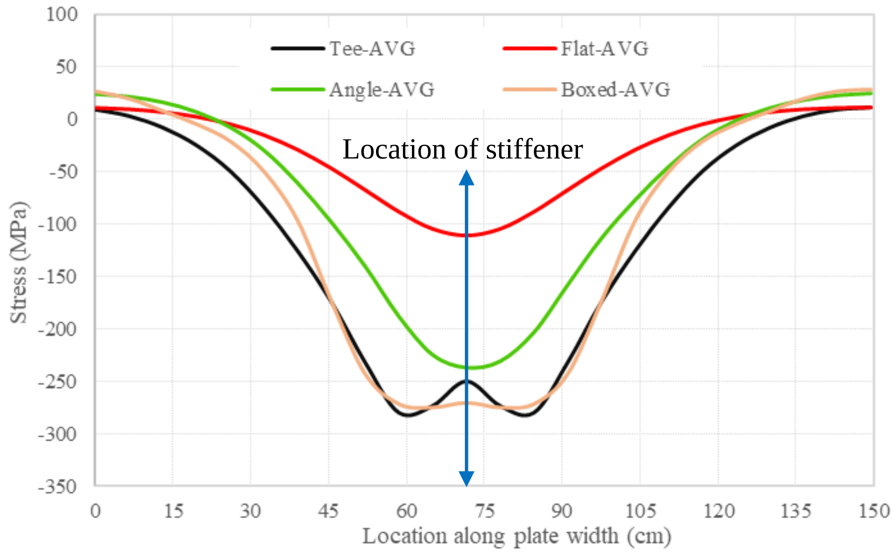


Figure 37: Average longitudinal stress through plate thickness for 150 cm spacing

3.4 Effect of Mesh Size on Effective Breadth Width

The effective breadth width is calculated based on the stress distribution along and through plate thickness spanning between the stiffeners, the mesh size along the plate effects the stress profile accuracy and hence the computed effective breadth width. To ensure that selected 60 mm nominal mesh size of the model is small enough, a mesh sensitive study was performed. For this purpose, the stiffened plate properties used in the study was given in Table 7. A tee section was selected as the stiffener with spacing of 150 cm. The length (span) of plate and width were taken as 800 cm and 760 cm respectively. The assumed boundary conditions and loading was consistent with the rest of cases presented. In other words, roller boundary condition and uniform pressure loading was assumed. For the mesh sensitivity study 2.5 cm, 4.0 cm, 5 cm, 6 cm and 12.5 cm mesh sizes were considered. For all models, the mesh size was the only variable and same boundary condition, loading, and material properties were used.

Table 7: Geometric properties of stiffened plate for mesh sensitivity

Type of Stiffener	Width, *B* (cm)	Length, *L* (cm)	Spacing (cm)	Web Thickness (mm)	Flange Thickness (mm)	Web Length (cm)	Flange Width (cm)
Tee	760	800	150	11.5	20	16	25

Figure 38 shows support reaction (applied load) versus plate vertical deflection at mid-span. The force displacement curves show that stiffened plates with all selected mesh sizes have similar results in terms of plate stiffness and out-of-plane load capacity. However, curve for the model with 12.5 cm mesh size, which is the largest mesh size considered for the analysis performed, shows negligible difference in the vicinity of yielding, which happens approximately at deflection of 10 cm. The models were loaded until significant plastic deformation was observed. For example, ductility corresponding to 80 cm vertical deflection is about 8. In summary, the presented force-displacement results show that the selected 6.0 cm mesh size is small enough the capture the behavior of stiffened plates studied.

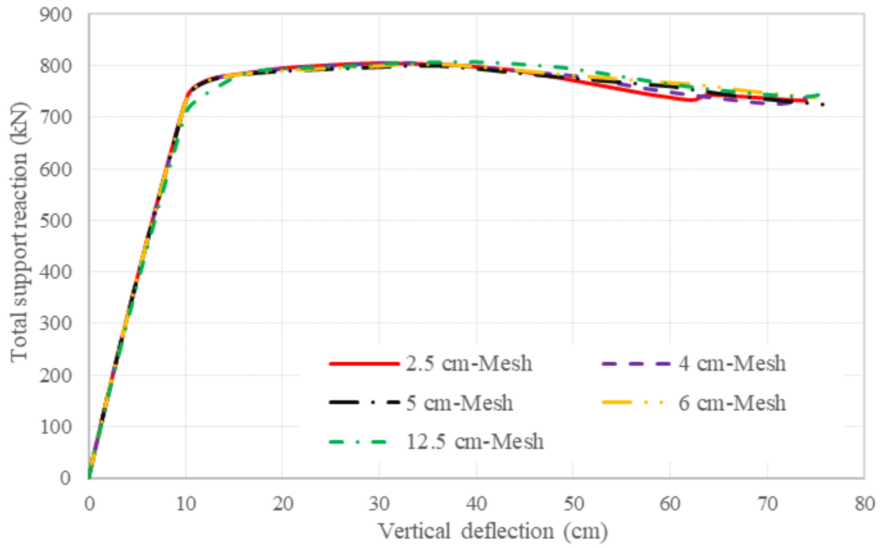


Figure 38: Reaction force versus displacement at mid-span of plate for different mesh sizes

Figure 39 shows computed effective breadth width for each selected mesh size at different stress levels (deflections). The results do not show any difference in computed effective breadth for deflection less than approximately 12 cm, which mostly correspond to elastic range. For deflections between approximately 12 cm and 40 cm, the breadth width predicted for 12.5 cm mesh was much larger than that computed using other meshes. However, the maximum average difference is not more than 20 cm. For plate deflection larger than 40 cm, which corresponds to large plastic deformations, the predicted breadth width was not much sensitive to mesh size and all computed breadth width values were approximately same. In conclusion, the results of mesh sensitivity analysis presented shows that selected mesh size 6.0 cm is adequate.

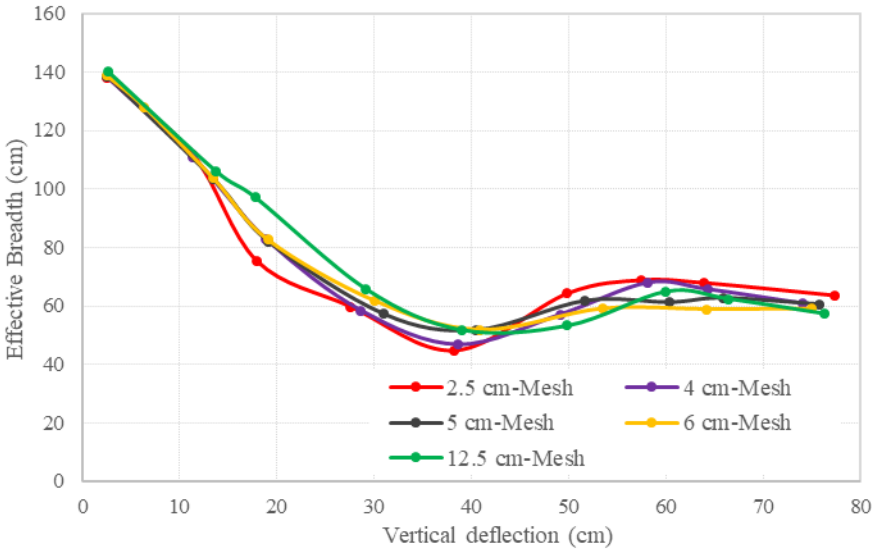


Figure 39: Effective breadth computed for different mesh sizes

CHAPTER IV

DETERMINATION AND VERIFICATION OF EFFECTIVE BREADTH BASED ON SIMPLE BEAM ANALYSIS

Although modelling whole stiffened plate structural system using finite element methods is a reliable approach to design and verify structural performance of selected stiffener and plate system, this approach is not practical and typically requires a significant amount of computational time. The finite element approach is also not economical due to high performance computer and typically experienced engineer needed. Therefore, simple beam approach also known as *"idealized beam"* approach is used with the predicted effective breadth to determine structural performance of the stiffened plate system. Typically, the idealized beam approach is used to design weld connections between the plate and stiffeners as well as plate support connections. However, the accuracy of this idealized beam approach with effective breadth has not been evaluated in the literature by comparing the structural performances computed with the idealized beam and full stiffened plate. In other words, the validity of using effective breadth to predict structural performance of stiffened plates has not been fully studied and verified.

In this chapter, the stiffened plate performance in terms of force-displacement was computed using full stiffened plate FE models, where both plate and all stiffeners were modelled using shell elements. In addition, force-displacement curves of the stiffened plate were also predicted using idealized beam models with several effective plate breadth values. The effective breadth values computed using plate stresses obtained from the stiffened plate full FE models were evaluated based on results of idealized beam by comparing force-displacement curves in terms of initial stiffness, yielding, and load carrying capacities.

4.1 Prototype Stiffened Plates and Simple Beams

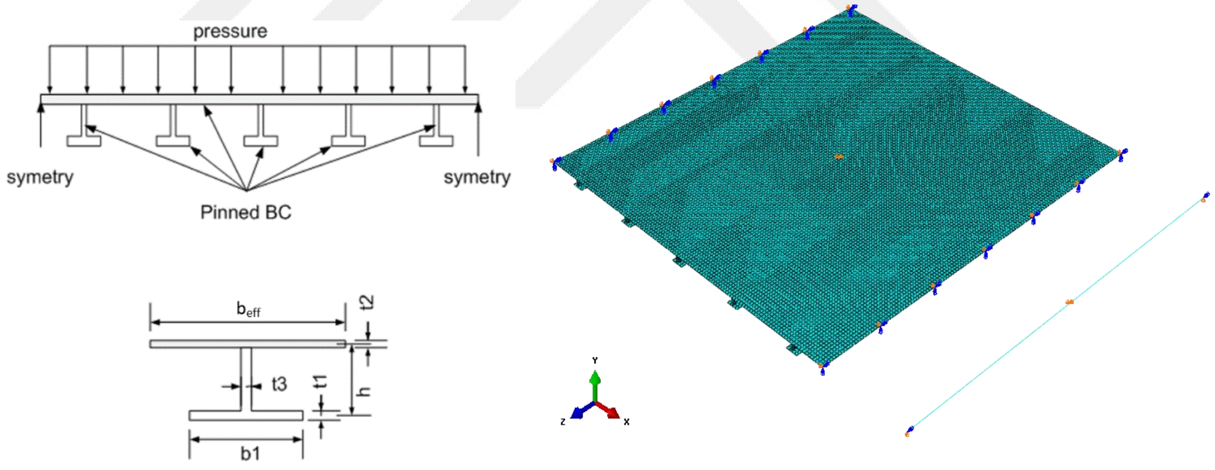
Three prototype stiffened plates (i.e., walls) were designed to investigate breadth width as given in Table 8. All walls had a span length *L* of 8.0 m and width *B* of 7.26 m. The walls were stiffened with five T-sections spaced equally at 1.5 m at center-to-center. Wall-A was designed to have plate and stiffener to yield approximately at the same out-of-plane (vertical) deflection. For Wall-B, stiffener flange thickness was almost doubled to 38 mm to force plate yielding to happen before stiffener yielding. To investigate stiffener yielding before plate yielding Wall-C was designed with a plate thickness of 20 mm, which is double of that assumed for Wall-A. Section properties of the walls are given in Table 8.

Table 8: Summary of wall sections

Wall ID	Structure Dimension (mm)			Section Dimensions (1) (mm)					Notes:
	B	L	b	t_1	t_2	t_3	h	b_1	
Wall-A	7620	8000	1524	20	10	12	160	255	Plate and flange yield at the same time
Wall-B				38	10	12	160	255	Plate yields first
Wall-C				20	20	12	160	255	Flange yields first

(1) dimension given in Figure 40 (a).

Figure 40 shows the FE model developed for full stiffened plate system and the idealized beam model or stick model. Finite element (FE) model of walls and idealized beam were created using general purpose Abaqus FE software. The plates and stiffeners were modelled using S4R shell element, which is a 4-node general-purpose shell element with reduced integration scheme and five integration points through thickness. The element is suitable for both thin and thick shells and includes membrane strain. The walls were loaded with uniform out-of-plane pressure as shown in Figure 40. The symmetry boundary condition was used along two edges of wall while roller boundary condition was defined through coupling at both ends of the walls to ignore membrane effects. A nominal mesh size of 60 mm was used for both models. The web thickness and span length of the walls were selected to ensure that yielding occurs at wall midspan due to bending. The idealized beam model was developed using Timoshenko B31 elements. The selected B31 element considers shear deformation and rotational bending effects, which enables to model short as well as long span beams accurately. Similarly, both ends of beam was assigned as roller boundary, and, loading was given as line load. Nominal mesh size was 60 mm, and I-type profile was assigned to the beam section. The developed full and idealized beam models are given in Figure 40.



(a) (b)

Figure 40: (a) Stiffened plate (b) FE model of plate and idealized beam

4.2 Effective Breadth Using Full and Idealized Beam Models

The effective breadth was calculated using three different approaches. First effective breadth (b_{e1}) was calculated using Winter [7] recommended expression as given in (Eq. 2.4). Because Winter expression is mostly developed for cold-formed steel plates and considered post-buckling behavior, the maximum plate stress in the expression was replaced with steel plate yielding stress. The second approach, effective breadth (b_{e2}) was calculated using analysis results from full stiffened plate model. Effective breadth for the stiffened plate was calculated using (Eq. 2.1) different plate stress levels obtained from the full stiffened plate model. In other words, the effective breadth was calculated at different plate displacement and stresses levels at both elastic and plastic ranges. Finally, in the third approach, the effective breadth (b_{e3}) was calculated using force versus displacement curves of plate determined using full plate and idealized beam FE models. For this purpose, the support reaction per stiffener versus plate midspan deflection curve of full model was compared with support reaction versus midspan deflection curve of the idealized beam for different plate effective breadth width values. The curves were compared in terms of initial stiffness, yielding, and load carrying capacity. The effective breadth width using the beam model was determined as that of the idealized beam, with force deflection curve best matching that of full stiffened plate model.

A summary of computed effective breadth values is given in Table 9. The results show that effective breadth width calculated using Winter formula is 38 cm for both Wall-A and Wall-B since the formula does not have stiffener flange thickness as a parameter, which is the only difference between the two walls. For Wall-C, the predicted effective breadth is 65 cm since the plate thickness was increased. These effective breadth widths with Winter expression were computed using plate yield stress as the maximum stress. In other words, the computed breadth values are for the plastic region, where structure undergoes significant plasticity.

Table 9: Summary of computed effective breadth using different formulae

Wall ID	Breadth Width (cm)		
	b_{e1} (1)	b_{e2} (2)	b_{e3} (3)
Wall-A	38	115 (75)	100-75
Wall-B	38	125 (70)	100-65
Wall-C	65	110 (50)	152-75

(1) compute per Winter formula in plastic region.
(2) computed based on stress distribution in elastic (plastic) regions using *(Eq. 2.1)*
(3) based on idealized beam force-displacement curves

The effective breadth values (b_{e2}) were calculated full stiffened plate stress values at different deflection and stress levels including elastic and plastic ranges of the plate vertical deflection. A summary of computed values for the elastic and plastic ranges are given in Table 9. In addition, the curves of effective breadth are given in Figure 41 through Figure 43 for all three stiffened plates. In the elastic range, in the vicinity of yielding, the effective breadth width values were computed approximately 115 cm, 125 cm, and 110 cm for Wall-A, Wall-B, and Wall-C respectively. However, as the analysis results indicate, the effective breadth values kept decreasing even after yielding deflection for all three walls. The decrease in effective breadth stopped and remained almost constant at vertical deflection of 20 cm, 15 cm, and 60 cm for Wall-A, Wall-B, and Wall-C, respectively. The difference in decreasing part of the curves especially that for Wall-C is considered to be due to increasing wall load even after wall yielding at approximately 10 cm. In the plastic range, where the effective breadth remained almost constant, the effective breadth values were computed as 75 cm, 70 cm, and 50 cm for Wall-A, Wall-B, and Wall-C respectively. In other words, the compute effective breadth values almost double of those predicted using Winter expression. In other words, the limited results indicate that Winter expression is significantly conservative for stiffened plates where the plate yields before the stiffener yields. However, the results for Wall-C indicate that Winter expression is slightly unconservative for stiffened plates where stiffener yields before the plate. The effective breadth curves computed for Wall-B and Wall-C also indicate that effective breadth slightly increase in plastic range once the minimum value is reached. This behavior has been contributed to stress redistribution in the plastic region, which results in the effective breadth width to remain relatively constant or even slightly increase. This phenomenon was also observed by Belenkiy et al. [22] for study done on stiffened plates used for ship structures.

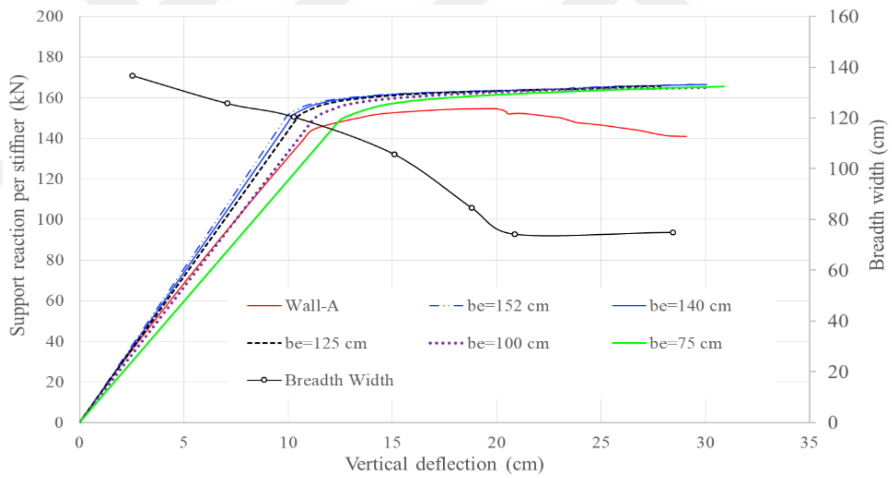


Figure 41: Support reaction versus vertical deflection at midspan for stiffened plate and idealized beam with different breadth width for Wall-A

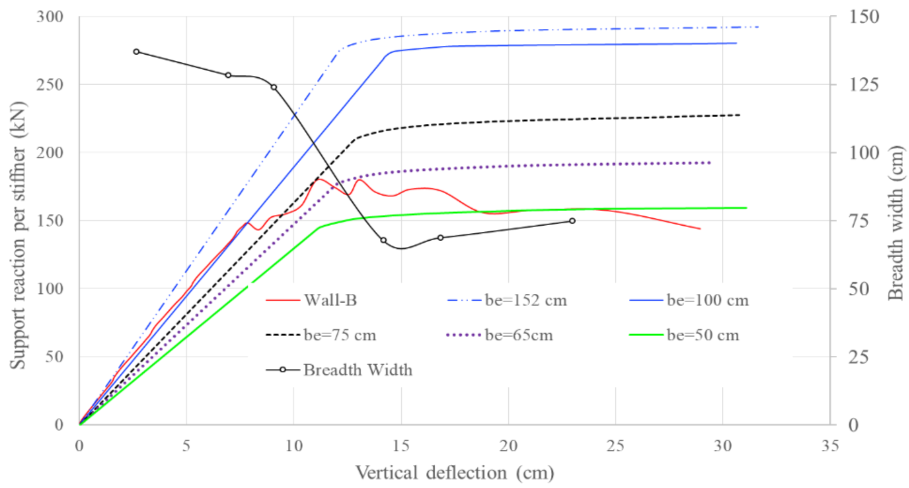


Figure 42: Support reaction versus vertical deflection at midspan for stiffened plate and idealized beam with different breadth width for Wall-B

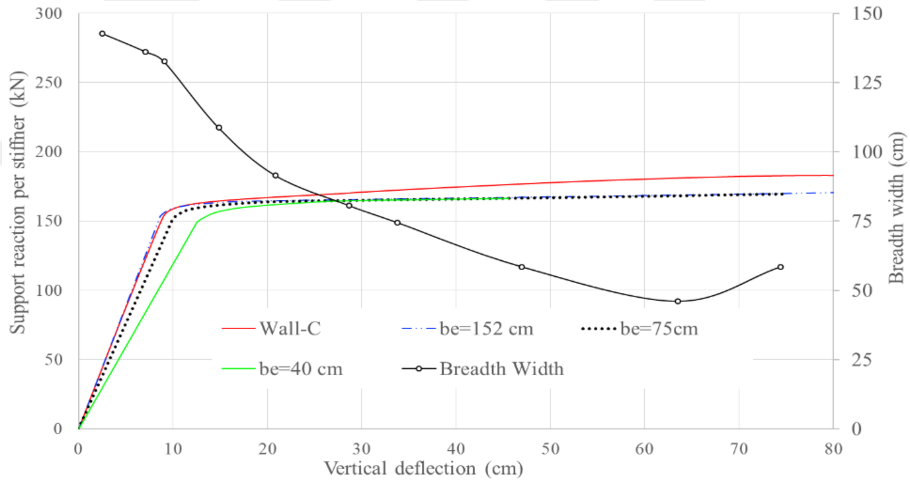


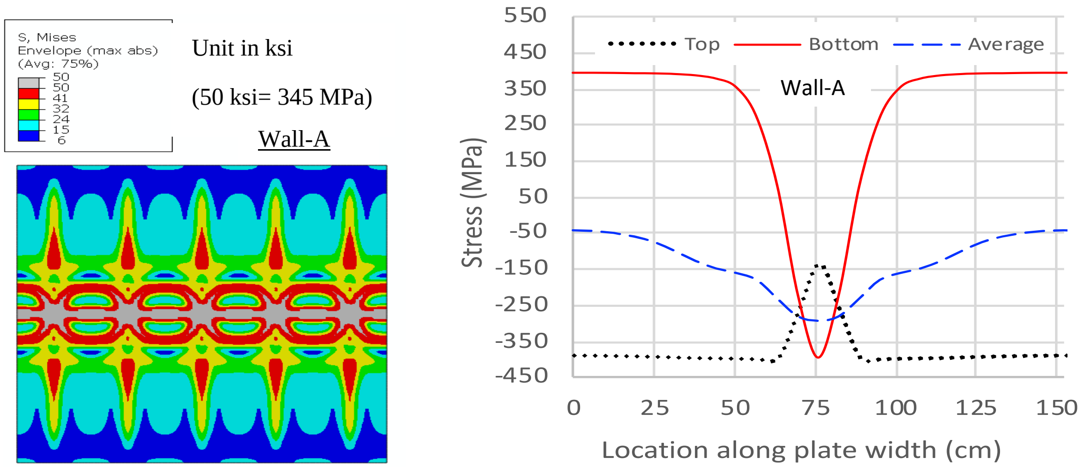
Figure 43: Support reaction versus vertical deflection at midspan for stiffened plate and idealized beam with different breadth width for Wall-C

The computed effective breadth width using force versus deflections curves of the plates and the corresponding idealized beams with different breadth widths is considered to be the most reliable method since this ensure that idealized beam can be used to predict wall deflection and support reaction (stiffness). For Wall-A, the beam with an effective breadth width of 100 cm was the only beam characterizing the wall especially in the elastic range (stiffness) as shown in Figure 41. However, the ultimate load carrying capacity of the beam was higher than the plate as much as 10 kN (less than 10%). However, since Wall-A plate thickness was only 10 mm, the idealized beam force-deflection curves were not very sensitive to the effective breadth width, and idealized beam with 75 cm breadth also had similar behavior especially in the plastic range. However, it should be noted that the decrease in plate load carrying capacity in the plastic range due to out of bending of plate was not captured as expected using the idealized beams. For Wall-B, the computed effective breadth was 100 cm for the elastic range based on stiffness in the elastic range, and only 65 cm in the plastic range based on load carrying capacity. However, it should be noted that Wall-B was designed to plate yielding before the stiffener flange yields. This selected behavior resulted in significant plastic deformation (strain) in plate, which caused out of plane local deflection. These out of plane deflections caused a decreased ductility capacity for the wall. In other words, the analysis results show that stiffened plate should be designed, and plate thickness should be selected such that the stiffener flange yields before the plate. For Wall-C, where stiffener yields before the plate, the beam effective breadth width was 152 cm for both elastic and plastic ranges. However, the response of the beam was not so sensitive to effective breadth as response with effective breadth of 75 cm was also reasonable in terms of both initial stiffness and load carrying capacity.

The limited number of stiffened walls tested in this section show that effective breadth calculated using Winter expression can be conservative (smaller) for the plastic range or for plates expected to go under significant plasticity. On the other hand, the effective breadth width values calculated using actual stress distribution through the plate are typically 50% higher and can justify more economic design for stiffened plates.

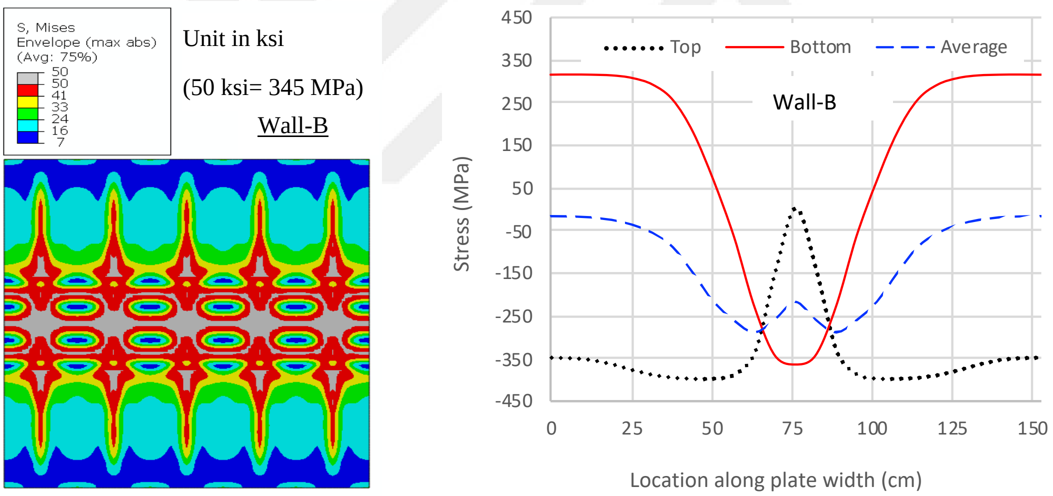
Figure 44 through Figure 46 show Von Misses stress envelope contours for the plates in the plastic range. The results show significant plasticity in the plate especially for Wall-A and Wall-B, where plate yields at the same time or before the stiffener flange yields. Especially stress contours for Wall-B, which was designed such that plate yields before the flange, show significant plasticity extending over a large area. The stress contours for Wall-C, which was designed such that stiffener flange yields before the plate, show that plastic stress contours are limited in the vicinity of stiffener, where the stiffener is connected to the plate. These stress results clearly show that such stiffened plate systems should be designed to have stiffener flange to yield before the plate to limit the damage in plate.

Figure 44 through Figure 46 also show stress profile recorded on plate top and bottom surfaces as well as average stress variation through plate between stiffeners. The results show that selection of stiffener and plate also significantly affects stress distribution in plate in the vicinity of stiffener. Complexity of stress profile is visible for Wall-A and Wall-B, where plate yields before or at the same with the stiffener flanges. The results also show that presence of stiffener change longitudinal stress direction in the vicinity of stiffener. Far away from stiffeners the plate top surface is under compression and bottom surface in under tension. However, over the stiffener the plate top surface and bottom surface both can be under compression depending on location of neutral axis. In other words, for plate far away from stiffeners the neutral axis is located in the middle plane while the neutral axis moves down towards the stiffener for plate in the vicinity of stiffener.



(a) (b)

Figure 44: Wall-A; a) Plate Misses stress contours, b) Longitudinal stress at plastic deformations along plate thickness



(a) (b)

Figure 45: Wall-B; a) Plate Misses stress contours, b) Longitudinal stress at plastic deformations along plate thickness

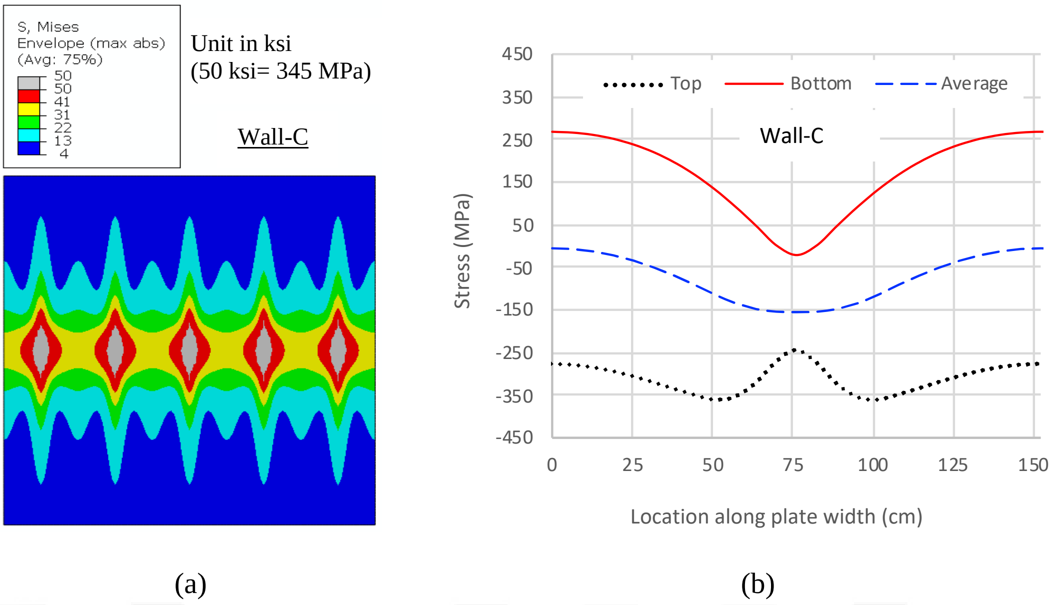


Figure 46: Wall-C; a) Plate Misses stress contours, b) Longitudinal stress at plastic deformations along plate thickness

CHAPTER V

SUMMARY, CONCLUSION AND FUTURE WORK

5.1 Summary

The thesis includes three main studies related to effective breadth width of stiffened steel plate structures, these are; finite element modelling of stiffened steel plates and determination of effective breadth using computed plate stresses, a parametric study on effective breadth of stiffened steel plate structures, where effects of plate thickness, spacing of stiffener, and type of stiffeners are investigated; and determination and evaluation of effective breadth using idealized simple beam.

In Chapter I, definition of effective breadth and its difference from effective width is given. A summary of studies both on effective width and breadth is included. In Chapter II, finite element modelling details of stiffened plate are discussed. In addition, the methodology adopted to calculate effective breadth using longitudinal stresses on plate top and bottom surfaces and middle plane is explained. Plate damage definition, which is expressed in terms of support rotation (slope) and ductility, is given to determine change of effective breadth at different damage levels. In Chapter III, a parametric study investigating effects of several design parameters on effective breadth was performed. The investigated parameters include plate thickness, spacing of stiffeners, type of stiffener, and mesh size. Finally, the validity of available two expressions used to predict effective breadth was evaluated for each parametric case.

In Chapter IV, a simple and cost-effective method known as idealized beam method was used to model the stiffened plate structure. Plate force versus deflection curves computed using idealized beam and full stiffened plate shell models were compared in terms of initial stiffness, yielding, and load carrying capacity. The effective breadth values computed using stiffened plate full FE shell models were evaluated based on results of idealized beam by comparing force-displacement curves. In other words, applicability of effective breadth, which is defined to be able to use idealized beam to predict response of stiffened plate, was evaluated.

5.2 Conclusions

The following conclusions can be derived from the present study on each subject studied.

Parametric Study on Effective Breadth of Stiffened Steel Plate Structures

- The available expression in the literature used to predict effective breadth are originally developed to predict effective width for cold-form steel sections. However, these expressions are typically used to predict effective breadth, too.
- The results presented show that both Bruhn and Winter expressions predict similar effective breadth values and they are in good agreement with the values computed in this study in the plastic range. However, in the elastic and transition regions (small plasticity), the computed values of breadth in this study are slightly larger than those predicted using Winter expression. Although Winter expression was developed for cold-formed stiffened plates and consider buckling of plate, the expression seems to be reasonable to predict effective breadth. One potential reason for Winter formula predicting smaller breadth width is very likely the fact that expression was developed

mainly considering plate post buckling behavior.

- The computed effective breadth values using computed longitudinal stress for plate are approximately 50% higher than those predicted using Winter or Bruhn expressions. Therefore, Winter and Bruhn expressions are typically conservative, and larger effective breadth values can be justified for both elastic and plastic ranges.

- The results of parametric study reveal that effective breadth value is highly sensitive to stiffener spacing, plate thickness and as well as type of stiffener. Increased stiffener spacing increased the effective breadth especially in the elastic or small plastic deformations. However, the effect of stiffener spacing decreased as plasticity or deformation of plate increased.

- Plate thickness seems to be one of the most important design parameters that affects effective breadth. The effective breadth increased with increasing plate thickness. The increase in effective breadth was negligible in the elastic range and at very large plastic deformations. However, effects of plate thickness were more significant for deformations associated with moderate plastic deformation corresponding a support slope deformation between 2 and 8 degrees. On the other hand, in the plastic range, the relationship between effective breadth and plate thickness were approximately linear.

- The type and geometric properties of stiffener were found to be one of the most important design parameters affecting force-deflection curves of the stiffened plates. However, for the effects of stiffeners type were negligible on effective breadth especially at elastic range and low plastic deformations.

However, at significant plastic deformations (support rotation more than 6 degrees) boxed and tee section stiffener effective breadth values increased approximately 10 to 20 cm.

- The mesh study was performed for nominal mesh size of 2.5 cm, 4 cm, 5 cm, 6 cm, and 12.5 cm. The computed force-deflection curves were not sensitive to the mesh size although curve predicted using 12.5cm mesh slightly diverged from the other curves. The effect of mesh size on computed breath values was negligible. Especially in the elastic and large plastic deformations the difference was almost negligible. Therefore, selected nominal mesh size of 6 cm is considered to be adequate.

Modelling of Stiffened Steel Plate Structures by Idealized Beam Method

- With the idealized beam method, which is cost-effective, computed effective breadth values were almost double of those predicted using Winter expression. In other words, the limited results indicate that Winter expression is significantly conservative for stiffened plates where the plate yields before the stiffener yields. However, the results for Wall-C indicate that Winter expression is slightly unconservative for stiffened plates where stiffener yields before the plate.

- The analysis results show that stiffened plate should be designed, and plate thickness should be selected such that the stiffener flange yields before the plate.

- The limited number of stiffened walls tested in this section show that effective breadth calculated using Winter expression can be conservative (smaller) for the plastic range or for plates expected to go under significant plasticity. On the other hand, the effective breadth width values calculated using actual stress distribution through the plate are typically 50% higher and can justify more economic design for stiffened plates.

- The analysis results show that for stiffened plates designed such that plate yields before the stiffener flange, the force deflection curves are not well predicted using idealized beam or using effective breadth width concept.

- Finally, stress contours show that selection of stiffener and plate significantly affects stress distribution in plate in the vicinity of stiffener. Stress profile in the vicinity of stiffener is much more complicated especially for cases where the plate yields before the stiffener flange.

5.3 Future Work

In the literature, although effective width concept has been deeply studied, the study regarding the effective breadth width is limited. To further expand the understanding of effective breadth concept for stiffened steel plate structures following proposed future works are planned.

- The wide range of different geometric and material models can be used to model stiffened steel plate structures to get more data points that are used to provide regression formula for such stiffened plates.

- A large parametric study is recommended to further evaluate applicability of Winter and other available expressions used to predict effective breadth. Such a database is needed to developed design curves for effective breadth to cover different cases and stiffened plates.

- One of the biggest challenges in the study of plate is the membrane effect that changes the stress distribution through the plate thickness. Since effective breadth is calculated based on this nonlinear stress distribution, impacts of membrane stress on effective breadth width is needed to be investigated.

- In this study, although boundary condition of both edges for stiffened steel plate structures are assumed as pinned or roller to prevent membrane effects, the effects of different boundary conditions should be investigated.

- All results presented in this study are based on out-of-plane monotonic loads, where the plate is under compression. The effect of cyclic loading where the plate is under tension and stiffener flange under compression should be investigated.

- The lading condition assumed in this study was static loading. However, typically stiffened plate structures are used for structures exposed to dynamic loads such as blast. Therefore, there is a need to determine applicability of breadth with expressions and concept under dynamic loading.

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