*Civil Engineering Infrastructures Journal, 52(1): 59 – 84, June 2019*
*Print ISSN: 2322-2093; Online ISSN: 2423-6691*
*DOI: 10.22059/ceij.2019.250273.1456*

# The Effect of the Slot Length on Beam Vertical Shear in I-Beams with Moment Connections

**Shabanzadeh, E.[1], Abdollahzadeh, G.R.[2*] and Naghipour, M.[3]**

[1] Ph.D. Student, Faculty of Civil Engineering, Babol Noshirvani University of Technology, Babol, Iran.
[2] Associate Professor, Faculty of Civil Engineering, Babol Noshirvani University of Technology, Babol, Iran.
[3] Professor, Faculty of Civil Engineering, Babol Noshirvani University of Technology, Babol, Iran.

Received: 14 Jan. 2018; Revised: 25 Dec. 2018; Accepted: 25 Dec. 2018

**ABSTRACT:** This paper evaluates the effect of slot existence with limited length between flanges and web junction of I-shaped beams at the region of moment connections on vertical force and shear stress distribution in beam flanges and web at connection section in comparison with classical theory of stress distribution. The main purpose of this research is to evaluate the efficiency of the slot in connections such as slotted web beam to column connection in modern age. The issue of the slot has many benefits but very little studies have been done on it. Accordingly, one hundred and twenty models with two moment connections under the concentrated static load in mid span have been made for doing parametric study in ANSYS Workbench finite element software. The linear static analysis was done on all constructed models. Variable parameters in these models for parametric study include slot length between flange and web junction in connection region (from 0 to 190 mm), beam length, beam section height and Poisson's ratio of beam material. In all models the amount of shear stress in section height over the section vertical axis in connection region and also the devoted contribution from force which goes to flanges and web under the concentrated load on mid span have been calculated. Performed studies have shown that vertical shear stress distribution in beam to column connection section with moment connection differs a lot from what is stated in mechanics of materials equations. Practically the available equations in regulations which state that web receives the entire vertical shear and ignore the contribution of flanges are not reliable. In addition, studies have shown that the slot existence in junction of web and flanges in connection section with limited length can has great effect on the quality of vertical shear stress distribution over the section of connection and also the slot existence has great effect on the reduction of shear stress in flanges and increase in shear stress in web according to classical theory. As a total result, nowadays slotted web beam to column connection can be used as a fantastic and simple idea to improve modern connections behavior.

**Keywords**: Moment Connection, Slot Length between Flanges and Web Junction, Vertical Shear Stress.

* Corresponding author. E-mail address: abdollahzadeh@nit.ac.ir

## INTRODUCTION

Direct beam to column connections by CJP groove weld, are very common even in today's modern connections, such as dog bone connection. Structures of many sizes are composed of elements which are welded together. These moment connections in their traditional form demand greater attention during construction and are often the source of building failures (Abdollahzadeh et al., 2014) to the extent that these failures led to the abolishment of these connections despite the simplicity of their implementation (Rahman et al., 2013).

The moment connection detail most commonly used in seismic regions in the US between 1970 and 1994 (prior to the Northridge earthquake) was the welded flange, welded or bolted-web connection. In this type of connection the beam flanges are connected to the column using complete joint penetration (CJP) groove welds while the beam web is welded or bolted to the column with or without shear plate (Ramirez et al., 2012). But extensive brittle damage at the beam-to-column flange groove welds in numerous steel moment resisting frames were observed during the 1994 Northridge and 1995 Kobe earthquakes (Morshedi et al., 2017). Consequently, for improving the seismic performance of the “pre-Northridge” steel connections, new strategies, such as slotted web steel beam-to-column connection (Vetr et al., 2012), changing the weld access hole (WAH) geometry, (Lewei et al., 2016), strengthening the beam at the column face by adding a haunch (Yu et al., 2002), using side plates (Jalali et al., 2012), utilizing external T stiffeners (Kang et al., 2013), using vertical and inclined rib plates (Goswami et al., 2009) and weakening the beam section at a proper distance from the column face were proposed and evaluated under cyclic loadings (Mahmoudi, et al., 2013). Providing structural shear (Nikoukalam et al., 2015) and flexural fuses utilizing welded and bolted splice plates (Valente et al., 2017), trimming the beam flanges (Iwankiw et al., 1996), reducing the beam web (Wilkinson et al., 2006) and reducing both the beam flanges and the web simultaneously (Maleki et al., 2012) are among different techniques used with the objective of weakening the beam section.

Undoubtedly, in addition to introducing modern connections, these unpredictable extensive fractures in connections of moment frames in Northridge earthquake, questioned the validity of the available contents and formulas in well-known regulations of the world (FEMA, 2000). Before careful analysis of damages, the prevailing opinion was the lack of sufficient skill in performing the buildings especially in steel connections had the most major role in damage of the buildings. But more exact studies indicated the regulations overlooked the real behavior of steel structures especially in their connections (Miller, 1998).

Unfortunately even in modern age, stress related problems are classical topics and still there are some shortcomings in analyzing the problems. Undoubtedly, these defects lead to a widespread failure of moment connections which happened in the mentioned earthquakes. Because they have the boundaries where stress and deformation co-exist, and the problem turns into a complex situation (Rahman et al., 2013). The elementary theories of mechanics of materials are unable to predict the stresses in these critical zones of engineering structures. They are very inadequate to give information regarding local stresses near the loads and near the supports of the beam even in initial loading steps (Ahmed et al., 1998). They are only approximately correct in some cases but most of the time, violate conditions which are brought to light by the more refined investigation of the theory of elasticity. Among the existing mathematical models for two dimensional boundary-value stress problems, the two displacement function approach (Uddin, 1966) and the stress function approach (Timoshenko and Goodier, 1979) are noticeable. The solution of practical problems started mainly after the introduction of Airy's stress function (Timoshenko and Goodier, 1979). But the difficulties involved in trying to solve practical problems using the stress function are pointed out by Uddin (1966) and also by Durelli et al. (1989). The shortcoming of $\emptyset$-formulation is that it accepts boundary conditions in terms of loading only. Boundary restraints specified in terms of u and v cannot be satisfactorily imposed on the stress function $\emptyset$. As most of the problems of elasticity are of mixed boundary conditions, this approach fails to provide any explicit understanding of the stress distribution in the region of restrained boundaries which are, in general, the most critical zones in terms of stress. Again, the two displacement function approach that is the u, v formulation involves finding two functions simultaneously from two second order elliptic partial differential equations (Uddin, 1966). But the simultaneous evaluation of two functions, satisfying two simultaneous differential equations, is extremely difficult and this problem becomes more serious when the boundary conditions are specified as a mixture of restraints and stresses. On the other side, serious attempts had been rarely made in the real stress distribution in this critical region. Although elasticity problems were formulated long before, exact solutions of practical problems are hardly available because of the inability of managing the boundary conditions imposed on them (Ahmed et al., 1998). In this regard after mentioned earthquakes and more detailed studies, research centers such as Seismic Structural Design Associates (SSDA) concluded that such connections in which actual behavior of connections is not considerable are fundamentally flawed and should not be used in new structures. In fact, evaluation of Pre-Northridge connections indicated that failures occurred suddenly during earthquake and often most of these failures appeared in the form of crack in the weld of beam flanges to column flange and these cracks gradually progress towards the column web (Ricles et al., 2001). The remarkable thing in these failures is that, the beginning of these failures mainly occurred in beam flanges. Experimental researches and finite element studies on the Pre-Northridge connections represent substantial concentrated stresses in the weld of beam flanges in connection section (Dubina et al., 2001).

As mentioned before, a lot of ideas in the forms of improved or modern connections were introduced to reduce the effect of stress concentration in moment connections. Usually the basic idea of designing of modern connections is to strengthen the connection region or contrast to weaken the beam in the vicinity of connection. In other words all these connections intended to prevent yielding or brittle fracture of connection weld with going plastic hinge away from connection section. But what is certain, there is unknown problem at the beam to column welded moment connection which is at odd with relations of mechanics of materials (Ahmed et al., 1998). In writer’s idea more ideal state in the discussion of connections is to recognize these shortcomings and deal with them in the form of modifying the connection geometry. What concluded from studies on stress distribution at connection sections after Northridge earthquake was that beams basic theory underlying design of structural members in valid regulations is very unable to predict and determine the correct stress distribution in welded connections.

Fortunately today with the development of finite element software a very good understanding of force, displacement and composition of boundary conditions is possible. Dow et al. (1990) introduced a new method of boundary conditions modeling that was based on Finite Difference method to solve the problem of cantilever beam under uniform load with fixed support. The main contradiction in comparison of the classical theory results and finite element result is that by using the classical theory concludes that in I-sections under vertical shear forces due to transverse loading most of the shear force is the portion of beam web due to its low thickness and the portion of beam flanges from this shear is very negligible due to their large width. But in fact in many cases especially in beams with stocky flanges it is observed that contrary to classical theory flanges receive a significant portion of vertical shear in moment connection region meanwhile middle of web is empty from vertical shear (Lee et al., 2000). Going away from the connection section despite constant cross-section total shear (in the beam under concentrated load in mid span) unlike the connection section, shear in flanges is negligible but in the middle of web vertical shear stress is maximum, exactly as parabolic distribution of shear stress that in classical theory is observed. Undoubtedly this wrong attitude in the mechanics of materials and designing regulations relationship could raise serious fractures particularly in the welded connections in critical conditions.

Slotted web beam to column connections, which improved many weaknesses of traditional moment connections, were introduced by Seismic Structural Design Associates (SSDA) in 2002. In Slotted web beam to column connections, it is believed that the separation of the beam flange from the beam web results in the separation of flange force from the beam web, which leads to the elimination of shear stress concentration in beam flanges despite the simplicity of its implementation (Vetr et al., 2012).

In this regard this research investigates the advantages of slot modeling between beam flanges and web junction and modifies the geometry of the beam section in connection region using ANSYS Workbench finite element software. Actually the aim is to show that with a relatively simple way (by slot modeling), the stress distribution in the beam web and flanges in moment connections becomes close to the classical theory. These advantages in this study are investigated with considering parameters such as vertical shear stress distribution in section height and the portion of vertical shear force assigned to the web and flanges.

## TECHNICAL INTRODUCTION OF PROBLEM

Analysis of stresses in an elastic body is generally a three-dimensional problem. But in the cases of plane stress or plane strain, the stress analysis of three-dimensional body can easily be resolved into two dimensional (Rahman et al., 2013). An effective way of dealing with many two dimensional problems is to introduce the Airy stress function ∅, an idea was brought to us by George Airy in 1862. The stresses are written in terms of this function and a new differential equation is obtained which can be solved. This idea is the basis of many available equations of mechanics of material. The Airy stress function components are written in the form (Kelly, 2013):

$$\sigma_{xx} = \frac{\partial^2 \emptyset}{\partial y^2} \tag{1}$$

$$\sigma_{yy} = \frac{\partial^2 \emptyset}{\partial x^2} \tag{2}$$

$$\sigma_{xy} = \frac{\partial^2 \emptyset}{\partial x \partial y} \tag{3}$$

Eqs. (1-3) already ensures that the equilibrium equations are satisfied. With combining this two dimensional compatibility relation and the stress-strain relations:

$$\text{Plane stress: } \left(\frac{\partial^4 \emptyset}{\partial x^4} + 2\frac{\partial^2 \emptyset}{\partial x^2 \partial y^2} + \frac{\partial^4 \emptyset}{\partial y^4}\right) = 0 \quad (4)$$

This equation is known as the biharmonic equation. The biharmonic equation is often written using the short-hand notation:

$$\nabla^4 \emptyset = 0 \quad (5)$$

By using the Airy stress function representation, the problem of determining the stresses in an elastic body is reduced to that of finding a solution to the biharmonic partial differential Eq. (4) whose derivatives satisfy certain boundary conditions. Note that the shortcomings of the Airy stress function are:

1- Lack of dependence on elastic constants (Young's modulus $E$ and Poisson's ratio $\vartheta$). Despite the fact that studies have shown that stress distribution in moment connections is affected by elastic constants and ignoring of them leads to erroneous estimates of the correct shear force and stress distribution at connection section. In the next sections of this research, this serious dependency will be shown.

2- Airy stress function accepts boundary conditions in terms of loading only and this is the source of many incorrect stress distribution evaluation in real situations especially in moment connections, in the other word in this method the effects of boundary conditions can be replaced by equivalent forces.

An example of these shortcomings in cantilever beam by an end load is as follows.

Figure 1 shows a rectangular beam subjected to a transverse force $V$ at the end $x = 0$. This beam has a fixed support at the end $x = a$, the horizontal boundaries $y = \pm h$ being traction free. The boundary conditions for this problem are most naturally written in the form:

$$\sigma_{xx} = 0\,;\; x = 0 \quad (6)$$

$$\sigma_{yy} = 0\,;\; y = \pm h \quad (7)$$

$$\sigma_{xy} = 0\,;\; y = \pm h \quad (8)$$

$$\int_{-h}^{+h} \sigma_{xy}\, dy = V\,;\; x = 0 \quad (9)$$

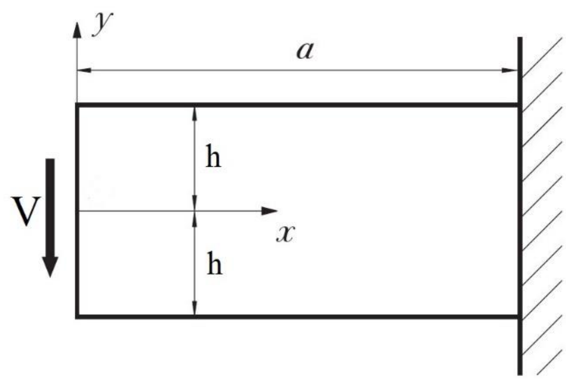


**Fig. 1.** Cantilever with an end load

The Airy stress function enables us to determine the stress components by applying the relations. Consider the Airy stress function as:

$$\emptyset = Axy^3 \quad (10)$$

$$\sigma_{xx} = \frac{\partial^2 \emptyset}{\partial y^2} = 6Axy \quad (11)$$

$$\sigma_{xy} = \frac{\partial^2 \emptyset}{\partial x \partial y} = -3Ay^2 \quad (12)$$

$$\sigma_{yy} = \frac{\partial^2 \emptyset}{\partial x^2} = 0 \quad (13)$$

From which we note that the boundary conditions (6) and (7) are satisfied identically, but Eq. (8) is not satisfied, since Eq. (12) implies the existence of an unwanted uniform shear traction $-3Ah^2$ on both of the edges $y = \pm h$. This unwanted traction can be removed by superposing an appropriate uniform shear stress, through the additional stress function term $Bxy$. Thus, if we define:

$$\emptyset = Axy^3 + Bxy \quad (14)$$

whilst Eq. (12) is modified to:

$$\sigma_{xy} = -3Ay^2 - B \quad (15)$$

The boundary condition (8) can now be satisfied if we choose $B$ to satisfy the equation:

$$B = -3Ah^2 \tag{16}$$

so that:

$$\sigma_{xy} = 3A(h^2 - y^2) \tag{17}$$

The constant $A$ can then be determined by substituting Eq. (17) into the remaining boundary condition (9), with the result:

$$A = \frac{V}{4h^3} \tag{18}$$

The final stress field is therefore defined through the stress function:

$$\emptyset = \frac{V(xy^3 - 3h^2xy)}{4h^3} \tag{19}$$

The corresponding stress components being:

$$\sigma_{xx} = \frac{3Vxy}{2h^3} \tag{20}$$

$$\sigma_{xy} = \frac{3V(h^2 - y^2)}{4h^3} \tag{21}$$

$$\sigma_{yy} = 0 \tag{22}$$

Of course, Eqs. (20-22) must be correct for the entire length of the beam, including at the fixed support.

Actually these last expressions agree with the elementary beam theory:

a) Bending stress distribution: $\sigma_{xx} = \frac{My}{I}$ (23)

b) Shear stress distribution:

$$\sigma_{xy} = \frac{V.Q}{I.t} \tag{24}$$

where *V*: is total value of the shear force at the section, *Q*: is static first moment of the area between the location where the shear stress is being calculated and the location where the shear stress is zero about the neutral axis, *I*: is the moment of inertia of the entire cross-section about the neutral axis and *t*: the width of the cross-section at the location where the shear stress is being calculated.

In fact the main focus of this research is based on the accuracy of the Eq. (24) at the moment connection section and the effect of the slot on it. This equation is the basic equation of mechanics of material in the case of vertical shear stress in the beams under transverse loading (Beer et al., 2014) which is obtained from the Airy stress functions.

According to Eq. (24), for example in I-beams maximum vertical shear stress occurs in the neutral axis and the amount of shear stress in the beam web is almost constant. On the other hand due to large width of flanges there is very small shear stress in them. For this reason according to the classical theory of shear stress distribution in I-beams total vertical shear stress is obtained by dividing total shear force in section into only the web area in the total length of the beam. Therefore based on the classical assumptions the approximate value of maximum shear stress in I-beams is only for web and is equal to (AISC, 2016):

$$\tau_{APPROX} = \frac{V}{A} \tag{25}$$

where *V*: is the total value of the shear force at the section and *A*: is the cross-sectional area of beam web only.

Eq. (25) is the basis for calculation of vertical shear stress in valid regulations. On one hand, regulations with this equation assume the portion of flanges from shear force is negligible, on the other hand they assume the shear distribution in the beam web is constant. But studies indicate that especially in the direct welded connections due to combined boundary conditions vertical shear stress real distribution in the beam is very different from the results of classical assumptions. These studies indicate a significant stress concentration in the flanges and negligible stress distribution in the web. Based on the researches the major reason for the appearance of such shear forces in the flanges are for the following items which are not considered in Airy stress functions (Lee et al., 2000):

1) The restraint of Poisson's effect at beam section in connection region which is equivalent to restraint of transverse strains and volume deformations, create a significant part of additional shear force at beam flanges.

2) Restraint of warping due to shear deformation in beam section at connection region especially in flanges due to boundary conditions creates another part of additional vertical shear force in the beam flanges.

The restraint of Poisson's and warping effects produce additional elastic strain energy due to self-straining in the beam cross-section near the support region. The shear strain due to restraint of Poisson's effects induces additional shear stress $\tau^{SP}$ and the shear strain due to restraint of warping induces additional shear stress $\tau^{SW}$ . Has be proven that shear stress due to restraint of Poisson's effect $\tau^{SP}$ and shear stress due to restraint of warping $\tau^{SW}$ in mid height of I-section cancel each other out, while these shear stresses in areas of the upper and lower sections, in flanges region have the effect of superposition (Lee et al., 2000).

On the other hand boundary effects for the I-beams are more complex than those for the rectangular sections because of interaction between the flanges and the web and the non-uniform stress distribution appears along the width of the flanges. The assumption is that because of the junction of flanges to web, flanges further restrained vertical warping in the web which is created by Poisson's effect near the support. As a result concentrated moments occur at the center of top and bottom flanges at connection section. These local moments create additional vertical shear stress in the flanges. Whole mentioned factors result in a significant redistribution of vertical shear stress in the connection section and lead to more crisis stress distribution in this region especially in the flanges. This article is supposed by decreasing restraint due to adjacent web and flanges with performance of slot with limited length can significantly reduce the amount of additional shear stress in the beam flanges at fixed connection (Lee et al., 2000).

## FINITE ELEMENT MODELING

In this article ANSYS Workbench Finite Element software was used to modeling. Since the purpose of research is determining the stress distribution at connection section in the elastic range, steel behavior is modeled to linear form with the Young's modulus of 200 Gpa and Poisson's ratio of 0.3 in the Finite Element models. The reason for modeling in linear mode is that, as mentioned, there is a serious problem in the moment connection section in elastic range of material which is exacerbated in times of crisis and leads to the failure of these connections. In all models force is static concentrated load and independent of time which is equal to 10000 N. This load applied on the upper flange in the center of beams. The force was applied in one step to all models. The main purpose was to obtain the amount of vertical shear force at top and bottom flanges and web and to determine the shear stress distribution at the connection section on the vertical symmetry axis of beam. Depending on the purpose of parametric study in this research variable parameters in the models are as follows:

1) The slot length of beam web and flanges junction at connection region from 0 to 190 mm

2) Beam span lengths equal to 2400, 3600, 4800, 6000 mm

3) Section heights equal to 220, 420, 620 mm

It is thought that those parameters can

affect the shear stress at connection region. The boundary condition is considered fixed connection by restraining all degrees of freedom at two ends. With the purpose of performing linear static analysis in the software and not performing buckling analysis, all of the models are not restrained laterally. Primarily because of software defaults in the static analysis buckling mode is not happening in linear static analysis. In order to achieve the best mesh size in models that have a minimum time of computer analysis and maximum convergence in analysis process, at first 5 models with different sizes of meshing were analyzed and their results finally compared with the results of classical theory in the quarter of span. It was observed that the elements with a size of 5 mm have an optimal response and therefore in all models this size of elements was selected for meshing. In all models, in the height of section and in the beam length virtual sensors were placed in flanges thickness and web height to determine the amount of vertical shear stress. On the other hand by using the ANSYS Workbench that has the ability of determine reaction forces at the components of support, the shear force at the top and bottom flange and web at connection section in supports is calculated. In models which the purpose is determining the effect of slot length on support shear force, slots with width of 1 mm and intended length in geometry of models were applied (Figures 1-2).

In order to perform parametric study in this research 120 models in which parameters such as slot length, span length and section height were variable were made. Specifications of any models are listed in Table 1. Each of the models has been named as Ba-b-c. In this naming a, b and c are the amount of section height, span length and slot length respectively in millimeter. It should be noted that in all models the thickness of flanges and web were considered 10 mm.

## VALIDATION OF FINITE ELEMENT MODELS

Due to the lack of experimental studies on determining the distribution of shear force and shear stress in reliable sources at the welded connection section, especially in slotted web beam to column connection, the validation of the ANSYS Workbench software modeling in this research was carried out in two ways. Of course, it is necessary to mention that, perhaps the reason for the lack of laboratory documentary results in the distribution of force and shear stress is the complexity of determining these parameters at the beam to the column connection section in the weld material.

### Validation with Experimental Tests of Zirakian (2007)

One of the most reliable full scale experimental studies that is available on lateral distortional buckling has been done by Zirakian (2007). Given that it has been proven in many studies that the results of these experimental tests are very reliable and accurate and also because of the lack of experimental studies on the distribution of force and shear stress at the connection section, especially in the case of slotted web beam to column connection, in this research at first the details of the ANSYS Workbench models, including geometric characteristics, materials properties, location of the supports, location of the lateral constraints, process of applying load, and the location of the displacement measurement exactly were extracted from the text of the Zirakian's research and in the ANSYS Workbench software models has been introduced to validate the modeling process.

The experimental beams in Zirakian's study, including two castellated and two equivalent plain-webbed full-scale simply supported steel I beams loaded with a central concentrated load applied at the upper surface of the top flange of the beam with an effective lateral brace at the mid span of the top compression flange (Figure 4) are considered in order to obtain comparison and evaluation. The purpose of this experimental study was to investigate the lateral distortional buckling mode of the 4 mentioned specimens. During the tests, lateral deflections of the section at three top flange, mid-height, and bottom flange levels were recorded at 1/4 point of the beam span by means of position transducers.

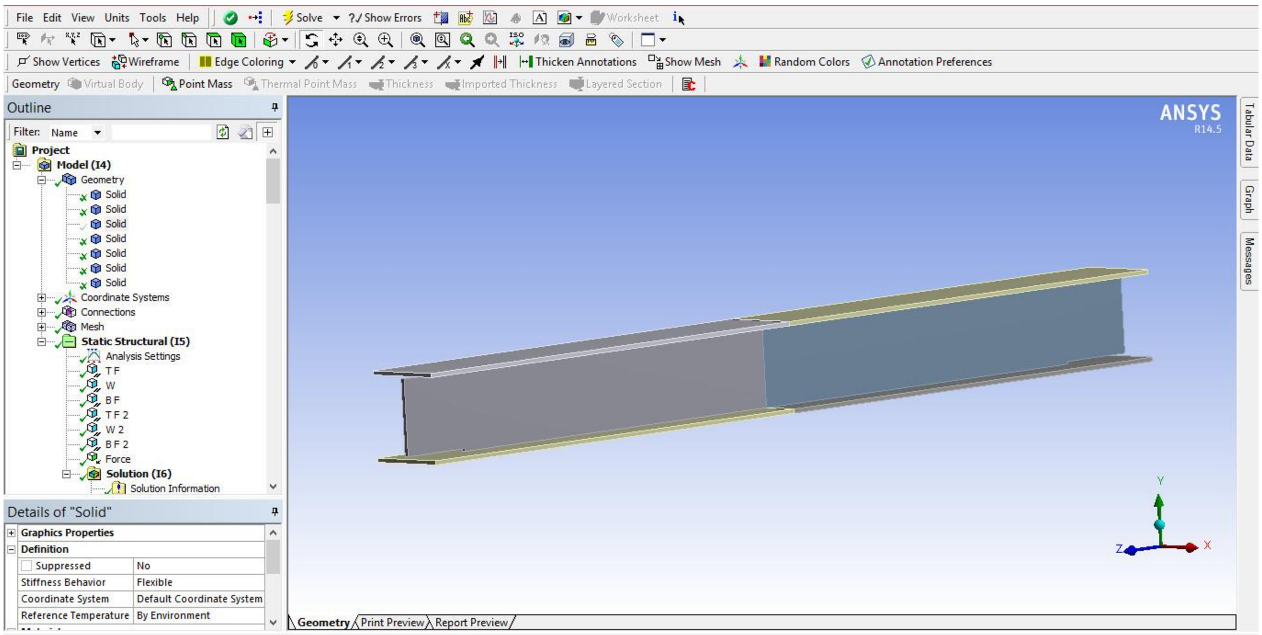


**Fig. 2.** General form of slotted models


**Fig. 3.** Total geometry of the slot

**Table 1.** Specifications of models in the parametric study

| Model name in group G1 | Model name in group G2 | Model name in group G3 |
|---|---|---|
| B220-2400-0 | B420-2400-0 | B620-2400-0 |
| B220-2400-10 | B420-2400-10 | B620-2400-10 |
| B220-2400-20 | B420-2400-20 | B620-2400-20 |
| B220-2400-40 | B420-2400-40 | B620-2400-40 |
| B220-2400-60 | B420-2400-60 | B620-2400-60 |
| B220-2400-80 | B420-2400-80 | B620-2400-80 |
| B220-2400-100 | B4200-2400-100 | B620-2400-100 |
| B220-2400-130 | B420-2400-130 | B620-2400-130 |
| B220-2400-160 | B420-2400-160 | B620-2400-160 |
| B220-2400-190 | B420-2400-190 | B620-2400-190 |
| B220-3600-0 | B420-3600-0 | B620-3600-0 |
| B220-3600-10 | B420-3600-10 | B620-3600-10 |
| B220-3600-20 | B420-3600-20 | B620-3600-20 |
| B220-3600-40 | B420-3600-40 | B620-3600-40 |
| B220-3600-60 | B420-3600-60 | B620-3600-60 |
| B220-3600-80 | B420-3600-80 | B620-3600-80 |
| B220-3600-100 | B420-3600-100 | B620-3600-100 |
| B220-3600-130 | B420-3600-130 | B620-3600-130 |
| B220-3600-160 | B420-3600-160 | B620-3600-160 |
| B220-3600-190 | B420-3600-190 | B620-3600-190 |
| B220-4800-0 | B420-4800-0 | B620-4800-0 |
| B220-4800-10 | B420-4800-10 | B620-4800-10 |
| B220-4800-20 | B420-4800-20 | B620-4800-20 |
| B220-4800-40 | B420-4800-40 | B620-4800-40 |
| B220-4800-60 | B420-4800-60 | B620-4800-60 |
| B220-4800-80 | B420-4800-80 | B620-4800-80 |
| B220-4800-100 | B420-4800-100 | B620-4800-100 |
| B220-4800-130 | B420-4800-130 | B620-4800-130 |
| B220-4800-160 | B420-4800-160 | B620-4800-160 |
| B220-4800-190 | B420-4800-190 | B620-4800-190 |
| B220-6000-0 | B420-6000-0 | B620-6000-0 |
| B220-6000-10 | B420-6000-10 | B620-6000-10 |
| B220-6000-20 | B420-6000-20 | B620-6000-20 |
| B220-6000-40 | B420-6000-40 | B620-6000-40 |
| B220-6000-60 | B420-6000-60 | B620-6000-60 |
| B220-6000-80 | B420-6000-80 | B620-6000-80 |
| B220-3600-100 | B420-3600-100 | B620-3600-100 |
| B220-6000-130 | B420-6000-130 | B620-6000-130 |
| B220-6000-160 | B420-6000-160 | B620-6000-160 |
| B220-6000-190 | B420-6000-190 | B620-6000-190 |

In order to validate the models of this research in terms of adaption with experimental tests results given that the main models in this study, which will come in later sections, are not castellated beam but they are two plain-webbed models. These models were made in ANSYS Workbench software, which their geometric specifications are given in Table 2.

**Table 2.** Cross-sectional dimensions of the test beams

| Model | h (mm) | b (mm) | s (mm) | t (mm) | L (mm) |
|---|---|---|---|---|---|
| P180 | 180 | 64 | 4.4 | 6.3 | 3600 |
| P210 | 210 | 73 | 4.7 | 6.9 | 3600 |

In Table 2, h, b, s, t, L are overall height of the section, width of the flanges, the thickness of beam web, the thickness of beam flange and the span length respectively. For example the general form of the model P180 is given in Figure 5. After modeling on each of the two models and after linear buckling analysis for each model, the nonlinear buckling analysis was performed by defining the initial defect based on the details mentioned in Zirakian's research. The final force was extracted from the results of Zirakian's tests in each similar model. These final forces were applied to the models in Ansys Workbench software by 15 substeps. By placing 3 virtual LVDT, lateral deflections at three top flange, mid-height, and bottom flange levels in each loading substeps were obtained. The lateral buckling mode in form of complete sine wave which was the result of the Zirakian's studies, both in linear buckling analysis and in nonlinear buckling analysis in this validation was observed. This sine wave deformation extracted from the analyzing of model P210 in ANSYS Workbench software is shown in Figure 6.

By extracting the lateral deflection at the mentioned points from software, the desired results obtained for validation. For example Figure 7 shows the results of model P210 in Zirakian's research, which was obtained from experimental tests. In this chart T.7, T.8 and T.9 are the lateral deflection of top flange, mid-height and bottom flange levels at quarter of beam span which are derived from experimental studies of Zirakian. Based on the models made to validate in this research, Figure 8 relates the validation results of the present study based on the Zirakian's similar model in ANSYS Workbench software. Investigating the results obtained from the software that relates to the material nonlinear behavior have very acceptable match to the results of Zirakian's experimental tests. This matching of the results in the P180 is also very significant and can confirm the accuracy of the next modeling process. The very few differences between the two charts are related to issues such as the exact amount of initial imperfection in the implementation, lab conditions and defects in loading devices, etc.

**Validation with Classic Equation**

In addition to validation based on laboratory tests, it is conceivable that the shear stress classic equation (Eq. (24)) in the solid mechanics can also be used to estimate the validity and accuracy of the research models.

In order to validation of the models, 4 beams with lengths of 2400, 3600, 4800 and 6000 mm located on two supports and all of them were under static concentrated load of 1000 N were made in ANSYS Workbench. Linear static analysis was performed on all of them. All beams have a height of 220 mm and a thickness of 10 mm for web and flanges and all the beams were made of steel. For every 4 models the amount of shear stress on neutral axis at a distance of 100 mm from supports both by using the vertical shear stress equation and by analysis software was calculated. For example for beam with a length of 2400 mm and a section height of 220 mm parameters of Eq. (24) in this article are derived as follow:

$V = 5000\ \text{N}$ , $Q = 260000\ mm^3$,
$I = 50800000\ mm^4$, $t = 10\ mm$

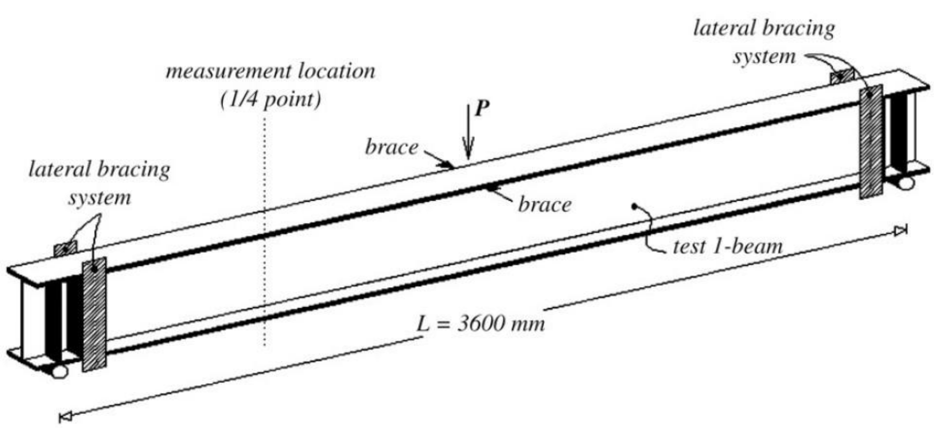


**Fig. 4.** Test setup of Zirakian's experimental research

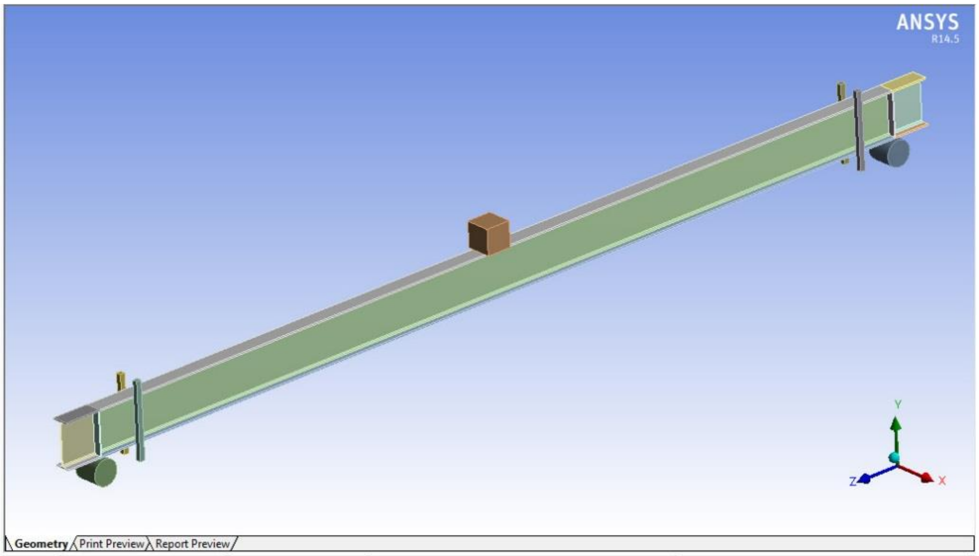


**Fig. 5.** A model made for validation

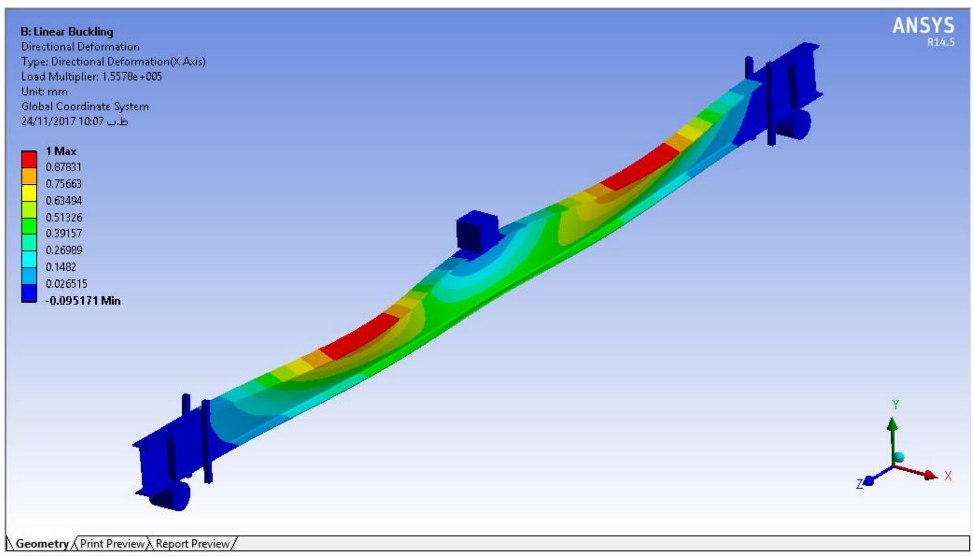


**Fig. 6.** Sine wave deformation of model P210 in validation

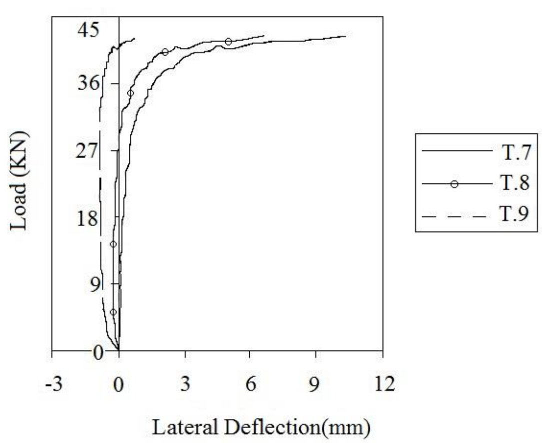


**Fig. 7.** Load–deflection curve of model P180 in Zirakian's experimental research

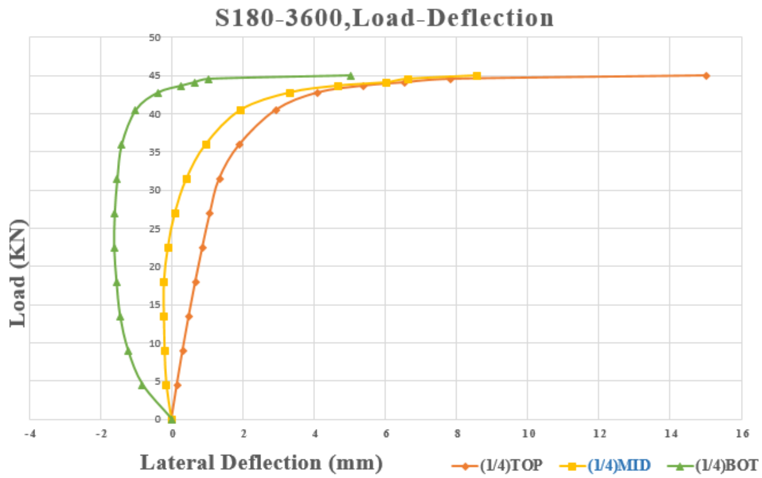


**Fig. 8.** Load–deflection curve of model P180 for validation

Using Eq. (24) the amount of vertical shear stress on the neutral axis and 4 decimal places is 2.5590 Mpa. Using ANSYS Workbench Finite Element software this value at a distance of 100 mm from support and with 4 decimal places is equal to 2.5588 Mpa that shows the accuracy of the modeling is acceptable.

## PARAMETRIC STUDY

ANSYS Workbench Finite Element software was used to perform parametric study. The main purpose of this parametric study is to estimate the effect of parameters such as slot length, span length and section height on vertical shear force and vertical shear stress at connection section. In this regard, 120 Finite Element models were constructed and parametric study was performed on them. According to Table 1 models were divided into three main groups denoted G1, G2 and G3. In each group there are 4 subgroups and in each subgroup there are 10 models. In each group constant parameter is beam span length. In every 10 models of each subgroup constant parameters are beam span length, and beam section height. In each model of each subgroup slot length varies with the growth of 0 to 190 mm which is shown in Table 1. The purpose of constructing each subgroup is to determine the effect of slot length on the vertical shear stress and vertical shear force assuming that beam span length and its section height are constant. In fact, by changing the subgroup in each group the span length is variable parameter. Because the assumption is that this parameter may also has a considerable impact on the vertical shear stress distribution and vertical shear force at the support region. By modeling 3 groups of forty which the effect of slot length and beam length were investigated, in each group a new group was created which section height was variable parameter and the effect of this parameter on stress distribution and vertical shear force were evaluated.

## RESULTS AND DISCUSSION

### Investigation of Vertical Shear Stress

Investigations of parametric study in all subgroups show that, in conventional connections, in which there is no slot between beam web and flange junction at connection region, distribution of shear stress at connection section significantly is different from the classical assumption of shear stress which is mentioned in mechanics of materials. An example of this result is presented in Figure 9. Following Figure 9, the maximum shear stress occurs in the outer fibers and the middle of web becomes free from stresses in the event that the results of classical assumption are exactly opposite. Moreover in all subgroups the results of studies indicate that in all un-slotted models, going away from connection section the stress distribution is closer to the classical assumption.

In Figure 10 an example of vertical shear stress distribution in model B220-2400-0 at a distance of 200 mm from support is presented. It is clear that not only the appearance of Figure 10 is very conforming to the appearance of classical stress distribution appearance but also the amount of stress is exactly equal to the result of the basic equation of mechanics of material which is mentioned in Eq. (24) of this research.

As mentioned in the previous sections the focus of this research is on the evaluation of slot length effect on shear stress distribution at connection section. In this regard, the results of all subgroups show that in all models increase in the slot length has a significant effect on decrease in the stress of outer fiber and increase in the stress of neutral axis and the results are coincided with the classical assumptions. But concerning the increase of neutral axis shear stress attention to this fact is necessary that increase of slot length to a certain extent has a significant effect on increasing the neutral axis shear stress, as far as in the beams with a lesser height a little more increase in the slot length causes reduction of neutral axis shear stress again.

Figure 11 presents increasing neutral axis shear stress in models with length of 2400 mm and height of 220, 420, 620 mm. The amounts of neutral axis shear stress and outer fiber shear stress are presented in Table 3. On one hand Figure 12 presents decreasing the outer fiber shear stress in models with length of 2400 mm and height of 220, 420, 620 mm.

In Figure 13 the effect of increasing slot length on vertical shear stress distribution at I-section height in the forms of shear stress graphs is presented. These models (B420-4800-0, B420-4800-40, B420-4800-100, and B420-4800-190) are the examples as shown in Figure 13. Like Figures 11 and 12 it can be concluded from Figure 13 that further increase of the slot length leads to increasing of neutral axis shear stress and decreasing of outer fiber shear stress. Figures 14-19 present the effect of slot on shear stress distribution in beam web and flange in software for some models.

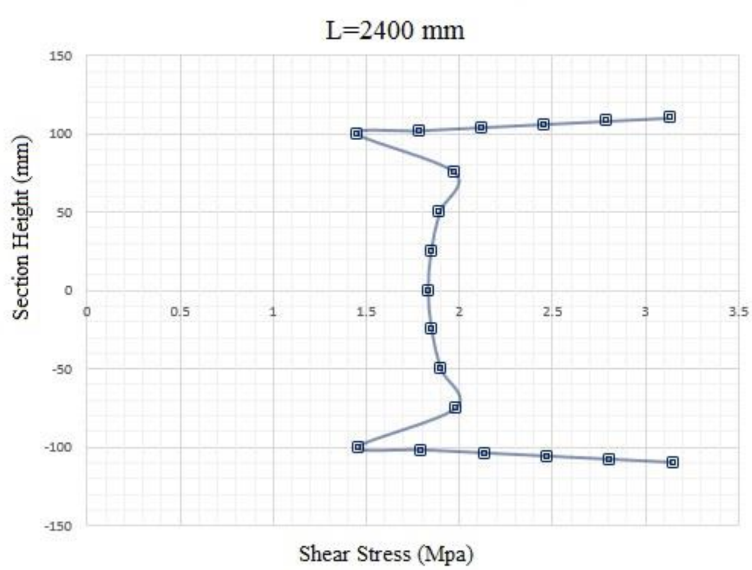


**Fig. 9.** Shear stress distribution at the cross section height in model B220-2400-0

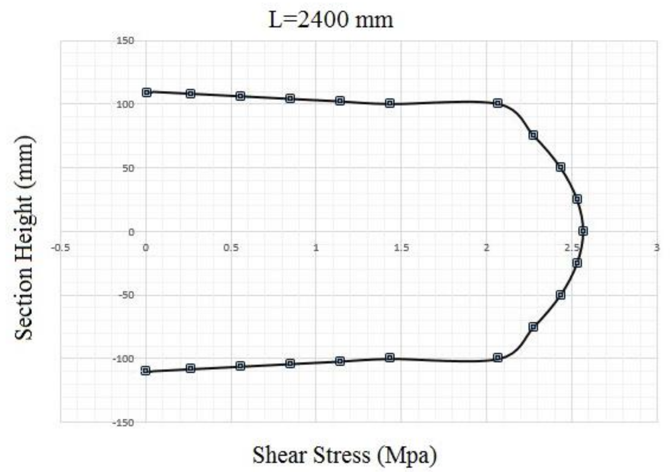


**Fig. 10.** Vertical shear stress distribution in model B220-2400-0 at a distance of 200 mm from support

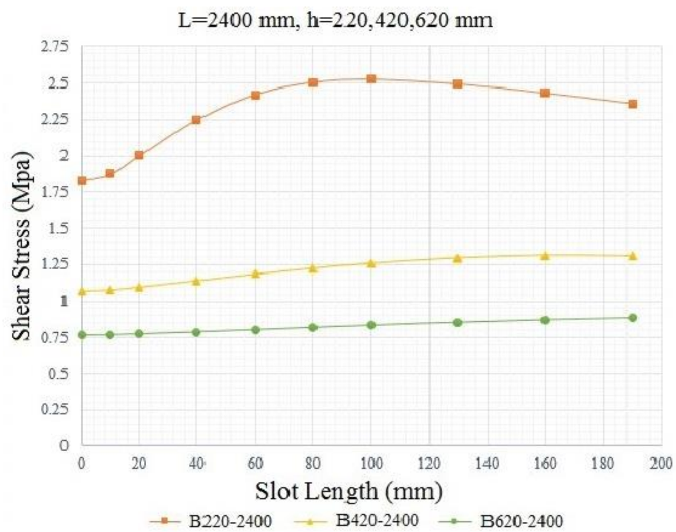


**Fig. 11.** The effect of slot length on increasing neutral axis shear stress

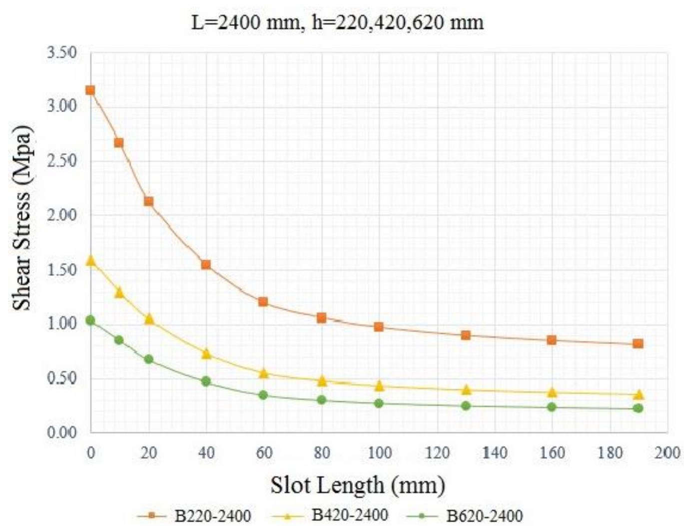


**Fig. 12.** The effect of slot length on decreasing outer fiber shear stress

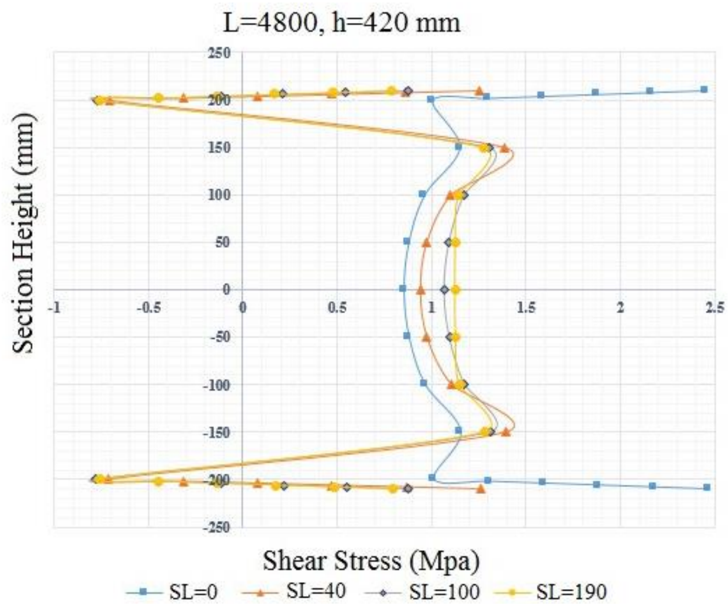


**Fig. 13.** The effect of increasing slot length on vertical shear stress distribution at section height

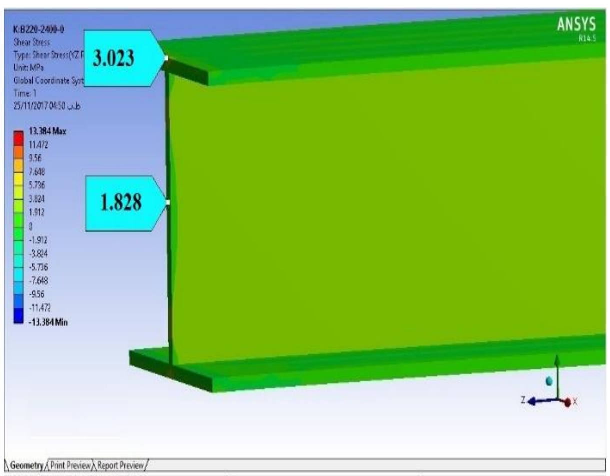


**Fig. 14.** Shear stress in model B220-2400-0

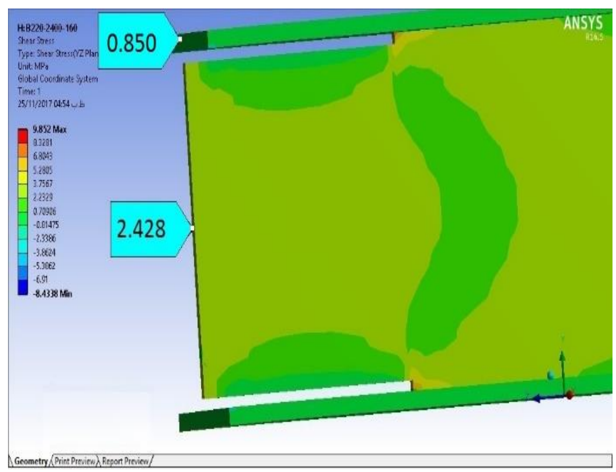


**Fig. 15.** Shear stress in model B220-2400-160

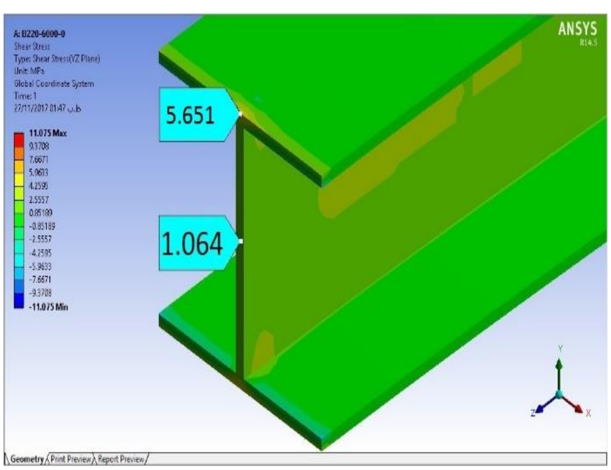


**Fig. 16.** Shear stress in model B220-6000-0

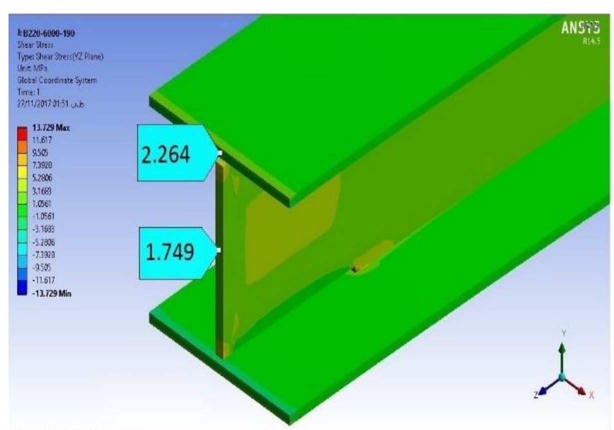


**Fig. 17.** Shear stress in model B220-6000-190

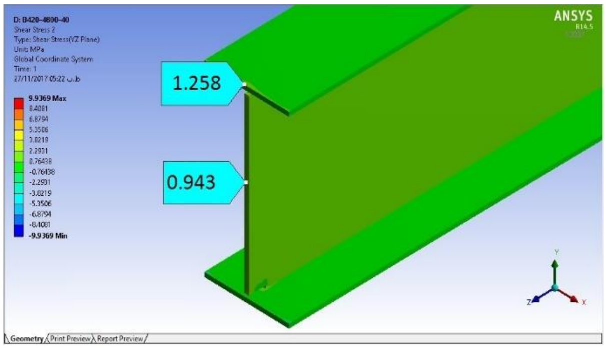


**Fig. 18.** Shear stress in model B420-4800-40

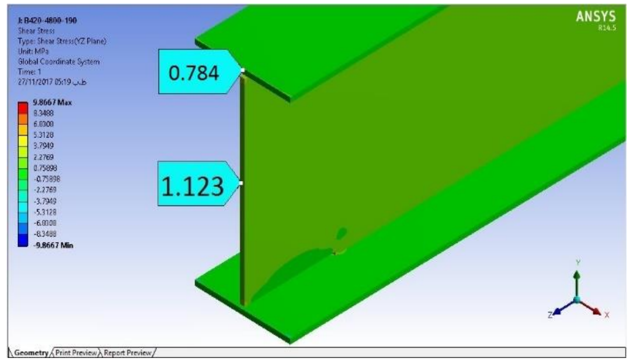


**Fig. 19.** Shear stress in model B420-4800-190

## Evaluation of Vertical Shear Force in Web and Flanges

As a matter of fact the evaluation of vertical shear force in connection section is summed up in three numbers: the shear force in top flange, web and bottom flange. Due to these parameters the critical state of connection section in ordinary and slotted connection is well seen and on the other hand the good effect of slot between web and flange junction in connections clearly evaluated. In Table 4 the portion of flanges and web shear force in all models in connection section is mentioned.

What is evident from Table 4 is that beam flange in connection section has the ability to get even to 45 percent of the total shear force of the section that it is quite evident in model B220-6000-0 and meanwhile due to lack of foresight in this event in regulations the weld of beam flange is not designed for this high shear and of course this case leads to the problem that in times of crisis connections experience serious failures. Certainly the minimum received shear force by the flanges between all models is about 10 percent and occurs in model B620-2400-0 which is any way a significant number and is not zero according to the classical theory. What is seen in all models about the benefits of the slot performance is that creating slot and increasing of its length in all models lead to decreasing the portion of flanges from vertical shear force and increasing the portion of web from this shear. Accordingly equations of regulations, assuming the shear of flanges is low, are closed to reality.

Of course the remarkable thing is that the rate of flanges shear reduction and web shear increase in the initial slot length is more and in further length of slot the change of flange and web portion is less sensitive to this parameter. Figures 20 and 21 respectively, present the change of flange and web portion from total shear force of connection section by increasing of slot length for example in models B220-2400-0 to B220-2400-190 .It should be noted that according to this study the general form of graphs is the same for all the made models.

## Evaluation of Beam Length on Vertical Shear Force in Web and Flange Section

Another main objective of the present study is to estimate the effect of beam length on web and flange shear force at connection section. By comparing the results it can be concluded that in each group the portion of flanges from shear force in models with less span length at a constant shear force is less than in models with more span length in other words in models with the same section height and the same slot length the more the span length becomes great, the more the portion of flanges from shear force becomes great. Of course it is worth mentioning that in models with greater span length and less slot length, the increase of the flanges portion from section total shear is very evident.

In long slot, due to the close similarity of force distribution to classical assumption at connection section, the flange does not generally share a lot of shear during different spans. These results are evident in Table 4. Change of flange shear force with change of beam span length for models B220-b-0 to B220-b-190 is presented in Figure 22. Contrary to the listed results about flanges, in each group the portion of flanges from total shear force at connection section in models with shorter beam length in a constant shear force is greater than the longer beam. In other words in models with the same section height and the same slot length when the span length becomes greater the portion of web from shear force becomes less and vice versa.

Of course it would be noted that similar to flanges discussion, decreasing the web portion from section total shear with the increase in beam span length in models with less slot length is very evident, because in long slot due to the close similarity force distribution to the classical assumption at connection section and basically in all models a lot of shear force is in the web. Changing the web shear force at connection section with changing of span length is presented in Figure 23 for models B220-b-0 to B220-b-190.

**Table 3.** The amounts of neutral axis shear stress and outer fiber shear stress according to change of slot length, beam span length and section height

| Model | Neutral axis shear stress (MPA) | Outer fiber shear stress (MPA) | Model | Neutral axis shear stress (MPA) | Outer fiber shear stress (MPA) | Model | Neutral axis shear stress (MPA) | Outer fiber shear stress (MPA) |
|---|---|---|---|---|---|---|---|---|
| B220-2400-0 | 1.8309 | 3.1480 | B420-2400-0 | 1.0731 | 1.5952 | B620-2400-0 | 0.7683 | 1.0382 |
| B220-2400-10 | 1.8755 | 2.6725 | B420-2400-10 | 1.0803 | 1.3069 | B620-2400-10 | 0.7707 | 0.8246 |
| B220-2400-20 | 2.0026 | 2.1331 | B420-2400-20 | 1.0994 | 1.0509 | B620-2400-20 | 0.7766 | 0.6766 |
| B220-2400-40 | 2.2505 | 1.5508 | B420-2400-40 | 1.1419 | 0.7365 | B620-2400-40 | 0.7898 | 0.4668 |
| B220-2400-60 | 2.4214 | 1.2007 | B420-2400-60 | 1.1855 | 0.5542 | B620-2400-60 | 0.8045 | 0.3459 |
| B220-2400-80 | 2.5033 | 1.0606 | B420-2400-80 | 1.2251 | 0.4819 | B620-2400-80 | 0.8196 | 0.2979 |
| B220-2400-100 | 2.5226 | 0.9751 | B4200-2400-100 | 1.258 | 0.4389 | B620-2400-100 | 0.8342 | 0.2693 |
| B220-2400-130 | 2.4918 | 0.8988 | B420-2400-130 | 1.2926 | 0.4013 | B620-2400-130 | 0.8543 | 0.2445 |
| B220-2400-160 | 2.4315 | 0.8503 | B420-2400-160 | 1.311 | 0.3777 | B620-2400-160 | 0.8711 | 0.2289 |
| B220-2400-190 | 2.3614 | 0.8136 | B420-2400-190 | 1.3061 | 0.3599 | B620-2400-190 | 0.8838 | 0.2172 |
| B220-3600-0 | 1.569 | 3.9993 | B420-3600-0 | 0.96168 | 2.0298 | B620-3600-0 | 0.7031 | 1.3149 |
| B220-3600-10 | 1.6242 | 3.3658 | B420-3600-10 | 0.97097 | 1.6284 | B620-3600-10 | 0.7062 | 1.0667 |
| B220-3600-20 | 1.7665 | 2.788 | B420-3600-20 | 0.99295 | 1.3697 | B620-3600-20 | 0.7130 | 0.8763 |
| B220-3600-40 | 2.0362 | 2.1106 | B420-3600-40 | 1.041 | 0.9972 | B620-3600-40 | 0.7284 | 0.6268 |
| B220-3600-60 | 2.214 | 1.7141 | B420-3600-60 | 1.0878 | 0.7875 | B620-3600-60 | 0.7446 | 0.4871 |
| B220-3600-80 | 2.298 | 1.5595 | B420-3600-80 | 1.129 | 0.7062 | B620-3600-80 | 0.7606 | 0.4327 |
| B220-3600-100 | 2.3185 | 1.4668 | B420-3600-100 | 1.1626 | 0.6588 | B620-3600-100 | 0.7760 | 0.4012 |
| B220-3600-130 | 2.2886 | 1.3862 | B420-3600-130 | 1.1971 | 0.6184 | B620-3600-130 | 0.7964 | 0.3743 |
| B220-3600-160 | 2.2303 | 1.3359 | B420-3600-160 | 1.2151 | 0.5935 | B620-3600-160 | 0.8133 | 0.3579 |
| B220-3600-190 | 2.1609 | 1.2985 | B420-3600-190 | 1.2112 | 0.5754 | B620-3600-190 | 0.8257 | 0.3460 |
| B220-4800-0 | 1.3083 | 4.8470 | B420-4800-0 | 0.85052 | 2.4662 | B620-4800-0 | 0.6383 | 1.5952 |
| B220-4800-10 | 1.3681 | 4.1265 | B420-4800-10 | 0.86059 | 1.9826 | B620-4800-10 | 0.6415 | 1.2835 |
| B220-4800-20 | 1.5303 | 3.4367 | B420-4800-20 | 0.88679 | 1.6889 | B620-4800-20 | 0.6498 | 1.0775 |
| B220-4800-40 | 1.8192 | 2.6731 | B420-4800-40 | 0.93968 | 1.2623 | B620-4800-40 | 0.6671 | 0.7905 |
| B220-4800-60 | 2.0053 | 2.2254 | B420-4800-60 | 0.99032 | 1.0212 | B620-4800-60 | 0.6850 | 0.6287 |
| B220-4800-80 | 2.0913 | 2.0568 | B420-4800-80 | 1.0332 | 0.9309 | B620-4800-80 | 0.7021 | 0.5678 |
| B220-4800-100 | 2.1127 | 1.9571 | B420-4800-100 | 1.0675 | 0.8790 | B620-4800-100 | 0.7180 | 0.5330 |
| B220-4800-130 | 2.0835 | 1.8727 | B420-4800-130 | 1.1017 | 0.8361 | B620-4800-130 | 0.73875 | 0.5043 |
| B220-4800-160 | 2.0269 | 1.8199 | B420-4800-160 | 1.1196 | 0.8097 | B620-4800-160 | 0.7558 | 0.4867 |
| B220-4800-190 | 1.958 | 1.7818 | B420-4800-190 | 1.1138 | 0.7911 | B620-4800-190 | 0.7680 | 0.4744 |
| B220-6000-0 | 1.0477 | 5.6955 | B420-6000-0 | 0.73948 | 2.9031 | B620-6000-0 | 0.5737 | 1.8761 |
| B220-6000-10 | 1.1149 | 4.8691 | B420-6000-10 | 0.75105 | 2.3586 | B620-6000-10 | 0.5772 | 1.5343 |
| B220-6000-20 | 1.2946 | 4.0847 | B420-6000-20 | 0.78078 | 2.0079 | B620-6000-20 | 0.5868 | 1.2788 |
| B220-6000-40 | 1.6036 | 3.2305 | B420-6000-40 | 0.83899 | 1.5245 | B620-6000-40 | 0.6061 | 0.9523 |
| B220-6000-60 | 1.7967 | 2.7367 | B420-6000-60 | 0.893 | 1.2549 | B620-6000-60 | 0.6256 | 0.7705 |
| B220-6000-80 | 1.8847 | 2.5541 | B420-6000-80 | 0.93761 | 1.1557 | B620-6000-80 | 0.6436 | 0.7031 |
| B220-3600-100 | 1.9071 | 2.4476 | B420-3600-100 | 0.97253 | 1.0995 | B620-3600-100 | 0.6602 | 0.6651 |
| B220-6000-130 | 1.8784 | 2.3588 | B420-6000-130 | 1.0065 | 1.0538 | B620-6000-130 | 0.6812 | 0.6343 |
| B220-6000-160 | 1.8236 | 2.304 | B420-6000-160 | 1.0241 | 1.0261 | B620-6000-160 | 0.6984 | 0.6157 |
| B220-6000-190 | 1.7551 | 2.2651 | B420-6000-190 | 1.0221 | 1.007 | B620-6000-190 | 0.7104 | 0.6030 |

**Table 4.** The portion of flanges and web shear force in all models at connection section according to change of slot length, beam span length and section height

| Model | Top flange force (N) | Web force (N) | Bottom flange force (N) | Model | Top flange force (N) | Web force (N) | Bottom flange force (N) | Model | Top flange force (N) | Web force (N) | Bottom flange force (N) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| B220-2400-0 | 692.35 | 3611.5 | 696.15 | B420-2400-0 | 356.85 | 4280.2 | 362.95 | B620-2400-0 | 230.09 | 4531 | 238.91 |
| B220-2400-10 | 581.24 | 3831.5 | 587.26 | B420-2400-10 | 303.49 | 4388.2 | 308.31 | B620-2400-10 | 197.59 | 4597.5 | 204.91 |
| B220-2400-20 | 411.5 | 4171.2 | 417.3 | B420-2400-20 | 214.17 | 4568.5 | 217.33 | B620-2400-20 | 139.76 | 4715.5 | 144.74 |
| B220-2400-40 | 250.28 | 4494 | 255.72 | B420-2400-40 | 126.86 | 4744.6 | 128.54 | B620-2400-40 | 82.599 | 4832 | 85.401 |
| B220-2400-60 | 171.67 | 4652 | 176.33 | B420-2400-60 | 83.92 | 4831.2 | 84.88 | B620-2400-60 | 54.352 | 4889.6 | 56.048 |
| B220-2400-80 | 128.49 | 4738.9 | 132.61 | B420-2400-80 | 60.309 | 4878.7 | 60.991 | B620-2400-80 | 38.759 | 4921.3 | 39.941 |
| B220-2400-100 | 101.74 | 4792.1 | 106.16 | B4200-2400-100 | 45.747 | 4908.1 | 46.153 | B620-2400-100 | 29.126 | 4940.9 | 29.974 |
| B220-2400-130 | 77.713 | 4839.5 | 82.787 | B420-2400-130 | 32.693 | 4934.3 | 33.007 | B620-2400-130 | 20.474 | 4958.5 | 21.026 |
| B220-2400-160 | 62.233 | 4869.9 | 67.867 | B420-2400-160 | 24.479 | 4950.9 | 24.621 | B620-2400-160 | 15.065 | 4969.5 | 15.435 |
| B220-2400-190 | 52.841 | 4888.5 | 58.659 | B420-2400-190 | 19.48 | 4960.9 | 19.62 | B620-2400-190 | 11.76 | 4976.2 | 12.04 |
| B220-3600-0 | 838.5 | 3320.4 | 841.1 | B420-3600-0 | 438.66 | 4118.7 | 442.64 | B620-3600-0 | 286.25 | 4422.5 | 291.25 |
| B220-3600-10 | 682.12 | 3633.9 | 683.98 | B420-3600-10 | 364.43 | 4268 | 367.57 | B620-3600-10 | 240.68 | 4514.6 | 244.72 |
| B220-3600-20 | 470.87 | 4057 | 472.13 | B420-3600-20 | 251.91 | 4494.1 | 253.99 | B620-3600-20 | 167.32 | 4662.7 | 169.98 |
| B220-3600-40 | 278.86 | 4441.6 | 279.54 | B420-3600-40 | 145.67 | 4707.6 | 146.73 | B620-3600-40 | 96.73 | 4805.1 | 98.17 |
| B220-3600-60 | 187.64 | 4624.4 | 187.96 | B420-3600-60 | 94.622 | 4810.1 | 95.278 | B620-3600-60 | 62.581 | 4874 | 63.419 |
| B220-3600-80 | 138.46 | 4722.9 | 138.64 | B420-3600-80 | 67.002 | 4865.6 | 67.398 | B620-3600-80 | 44.002 | 4911.4 | 44.598 |
| B220-3600-100 | 108.47 | 4782.9 | 108.63 | B420-3600-100 | 50.203 | 4899.3 | 50.497 | B620-3600-100 | 32.669 | 4940 | 27.331 |
| B220-3600-130 | 81.896 | 4836.1 | 82.004 | B420-3600-130 | 35.356 | 4929.1 | 35.544 | B620-3600-130 | 22.622 | 4954.5 | 22.878 |
| B220-3600-160 | 65.013 | 4869.9 | 65.087 | B420-3600-160 | 26.175 | 4947.5 | 26.325 | B620-3600-160 | 16.449 | 4966.9 | 16.651 |
| B220-3600-190 | 54.973 | 4890 | 55.027 | B420-3600-190 | 20.707 | 4958.5 | 20.793 | B620-3600-190 | 12.757 | 4974.4 | 12.843 |
| B220-4800-0 | 980.36 | 3037.3 | 982.34 | B420-4800-0 | 519.23 | 3958.6 | 522.17 | B620-4800-0 | 344.3 | 4315.1 | 340.57 |
| B220-4800-10 | 784.89 | 3428.8 | 786.31 | B420-4800-10 | 426.89 | 4143.9 | 429.21 | B620-4800-10 | 287.05 | 4428.9 | 284.05 |
| B220-4800-20 | 528.92 | 3941.2 | 529.88 | B420-4800-20 | 289.12 | 4420.2 | 290.68 | B620-4800-20 | 195.83 | 4610.3 | 193.84 |
| B220-4800-40 | 307.82 | 4383.9 | 308.28 | B420-4800-40 | 164.92 | 4669.3 | 165.78 | B620-4800-40 | 111.85 | 4777.4 | 110.77 |
| B220-4800-60 | 203.13 | 4593.5 | 203.37 | B420-4800-60 | 105.16 | 4789.2 | 105.64 | B620-4800-60 | 71.073 | 4858.5 | 70.421 |
| B220-4800-80 | 148.11 | 4703.6 | 148.29 | B420-4800-80 | 73.588 | 4852.5 | 73.912 | B620-4800-80 | 49.401 | 4901.6 | 48.972 |
| B220-4800-100 | 114.94 | 4770 | 115.06 | B420-4800-100 | 54.587 | 4890.6 | 54.813 | B620-4800-100 | 36.308 | 4927.7 | 36.01 |
| B220-4800-130 | 86.162 | 4827.6 | 86.238 | B420-4800-130 | 38.122 | 4923.6 | 38.278 | B620-4800-130 | 24.919 | 4950.3 | 24.732 |
| B220-4800-160 | 67.645 | 4864.7 | 67.655 | B420-4800-160 | 27.841 | 4944.2 | 27.959 | B620-4800-160 | 17.851 | 4964.4 | 17.729 |
| B220-4800-190 | 56.917 | 4886.1 | 56.983 | B420-4800-190 | 21.88 | 4956.2 | 21.92 | B620-4800-190 | 13.734 | 4972.6 | 13.649 |
| B220-6000-0 | 1121.2 | 2755.9 | 1122.9 | B420-6000-0 | 599.1 | 3799.4 | 601.5 | B620-6000-0 | 394.26 | 4208.5 | 397.24 |
| B220-6000-10 | 885.48 | 3228 | 886.52 | B420-6000-10 | 487.8 | 4022.5 | 489.7 | B620-6000-10 | 326.14 | 4345.3 | 328.56 |
| B220-6000-20 | 586.7 | 3825.9 | 587.4 | B420-6000-20 | 326.08 | 4346.6 | 327.32 | B620-6000-20 | 220.08 | 4558.2 | 221.72 |
| B220-6000-40 | 335.82 | 4328 | 336.18 | B420-6000-40 | 183.53 | 4632.3 | 184.17 | B620-6000-40 | 124.31 | 4750.5 | 125.19 |
| B220-6000-60 | 218.54 | 4562.7 | 218.76 | B420-6000-60 | 115.62 | 4768.4 | 115.98 | B620-6000-60 | 78.178 | 4843.1 | 78.722 |
| B220-6000-80 | 157.7 | 4684.5 | 157.8 | B420-6000-80 | 80.126 | 4839.5 | 80.374 | B620-6000-80 | 53.888 | 4891.9 | 54.212 |
| B220-3600-100 | 121.38 | 4757.2 | 121.42 | B420-3600-100 | 58.938 | 4882 | 59.062 | B620-3600-100 | 39.314 | 4921.1 | 39.586 |
| B220-6000-130 | 90.213 | 4819.5 | 90.287 | B420-6000-130 | 40.764 | 4918.4 | 40.836 | B620-6000-130 | 26.746 | 4946.4 | 26.854 |
| B220-6000-160 | 70.265 | 4859.4 | 70.335 | B420-6000-160 | 29.495 | 4940.9 | 29.605 | B620-6000-160 | 18.994 | 4961.9 | 19.106 |
| B220-6000-190 | 58.857 | 4882.3 | 58.843 | B420-6000-190 | 23.046 | 4953.9 | 23.054 | B620-6000-190 | 14.531 | 4970.9 | 14.569 |

## The Effect of Section Height on Flange and Web Vertical Shear Force

As mentioned in the introduction another purpose of present parametric study is to investigate the effect of I-beam section height on shear force distribution between flanges and web. Nevertheless increasing the portion of web from section shear is evident with increasing the slot length with comparison of results of models with the same span length and the same slot length but with different section height it can be said that as the section height becomes greater due to increasing the web height, flanges portion from section shear is diminished (Figure 24) and on the contrary web portion will be greater (Figure 25). The results for all similar models are visible in Table 4.

Similar to impact of beam span length at shear of connection section, it can be said that reduction of the portion of web and increase of the portion of flanges from section total shear force by increasing the height of the beam, in models with lesser slot length is very evident and in long slot due to the close similarity of force and stress distribution to the classical assumptions at connection section generally in different heights of section there is not a lot of force portion in the flanges and the major shear force is the portion of web and this result is evident in Figures 24 and 25. Increasing the portion of web and decrease the portion of flanges from section total shear with increasing span length for models Ba-3600-0 to Ba-3600-190 are presented in Figures 24 and 25, respectively.

## THE EFFECT OF SLOT ON THE BENDING MOMENT AT THE CONNECTION SECTION

As noted in pervious sections the existence of slot in the flange and web junction of the beam in spite of simple geometry and ease of implementation is underlain the appearance of considerable aspects in terms of force and stress distribution at moment connection section and could approximate the result of classical stress distribution and what really happens.

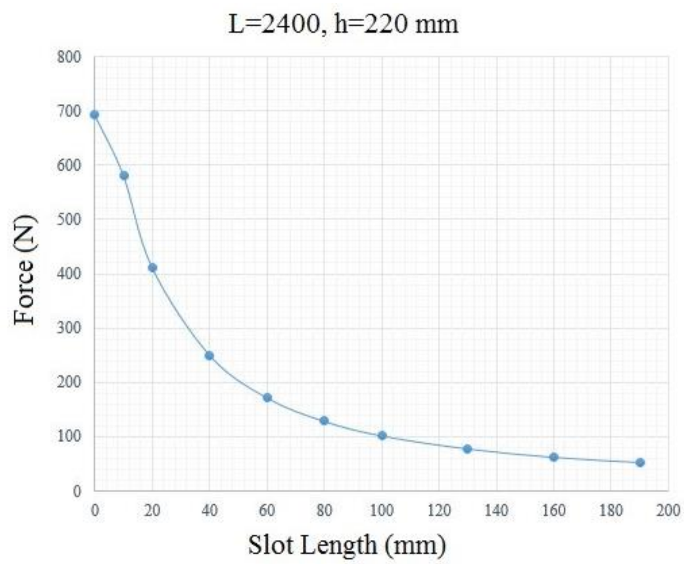


**Fig. 20.** The portion of top (bottom) flange from total shear force at connection section by increasing slot length in models B220-2400-0 to B220-2400-190

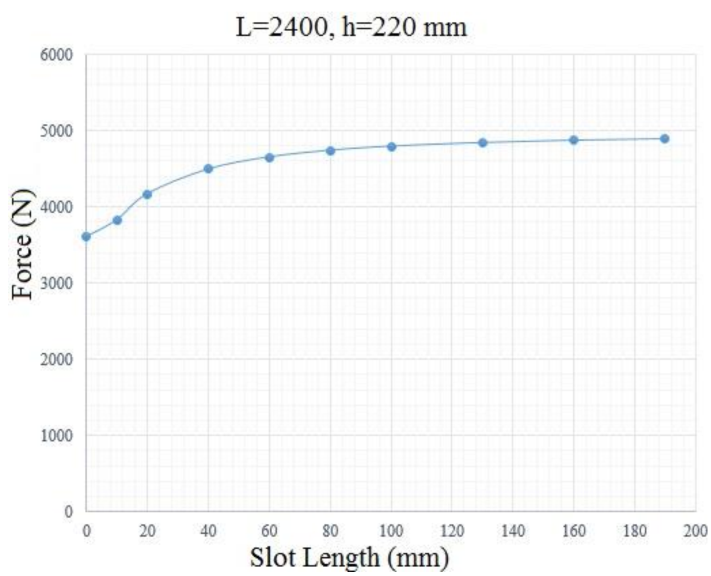


**Fig. 21.** The portion of web from total shear force at connection section by increasing slot length in models B220-2400-0 to B220-2400-190

But the important thing to be reviewed is that whether the slot leads to poor beam connection performance or not, especially in terms of resisting moment. In this regard bending moments in all slotted and un-slotted models were calculated and were compared with each other. The existence of slot in the web and flange junction at the connection region in addition to improving the state of shear stress and force distribution, in each subgroup leads to reducing the existing moment at the connection section. In other words in each subgroup despite the equality of geometrical parameters and applied load just by performance of slot fewer existing moment can be applied to the connection section.

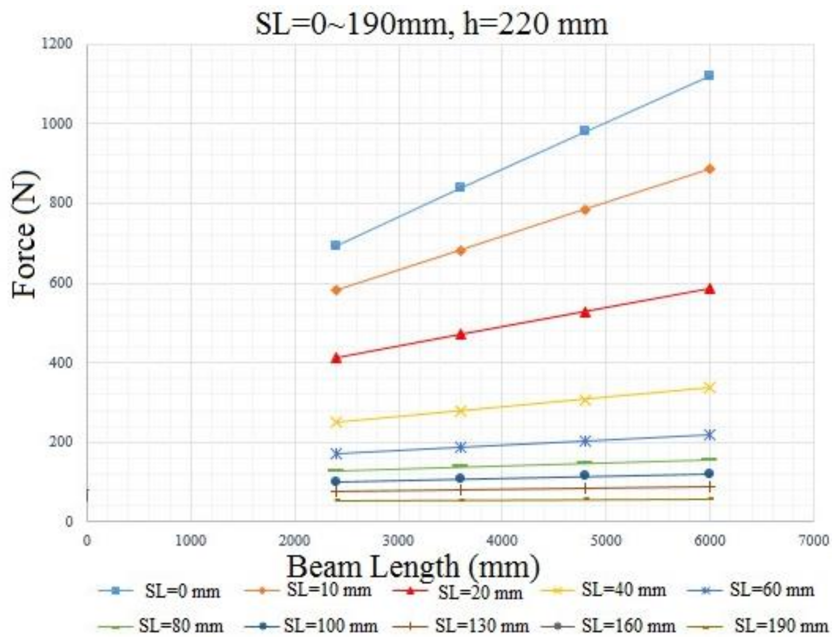


**Fig. 22.** Change of flange shear force from section total shear with change of beam span length for models B220-b-0 to B220-b-190 (b = 2400, 3600, 4800 and 6000 mm)

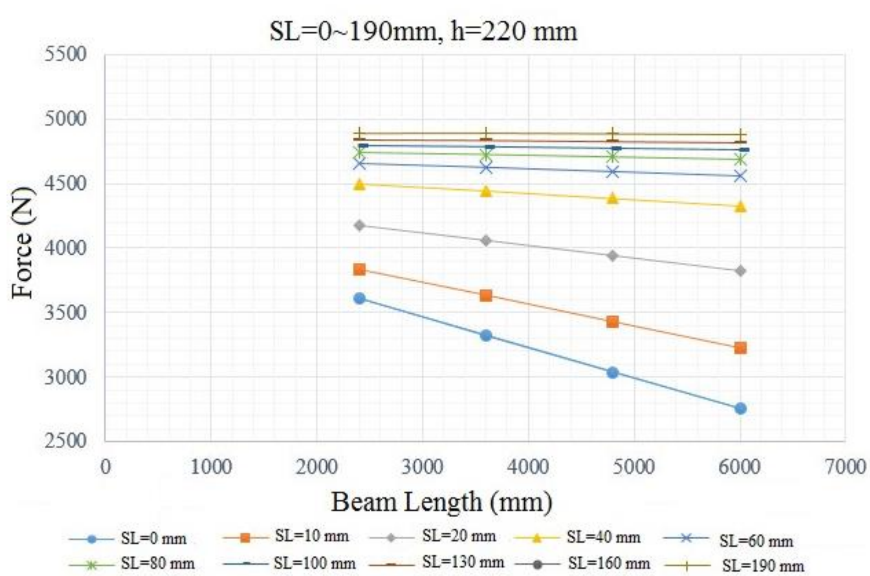


**Fig. 23.** Change of web shear force from section total shear with change of beam span length for models B220-b-0 to B220-b-190 (b = 2400, 3600, 4800 and 6000 mm)

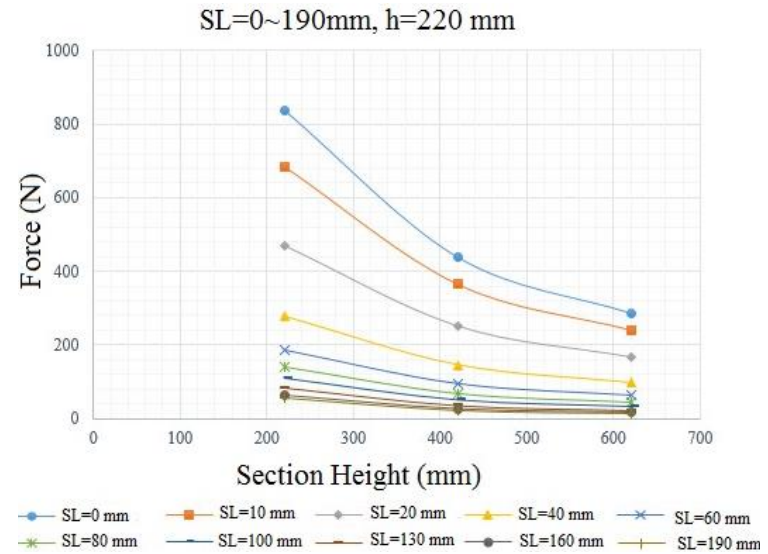


**Fig. 24.** Change of flange shear force from section total shear with change of beam section height for models Ba-3600-0 to Ba-3600-190 (a = 220, 420 and 620 mm)

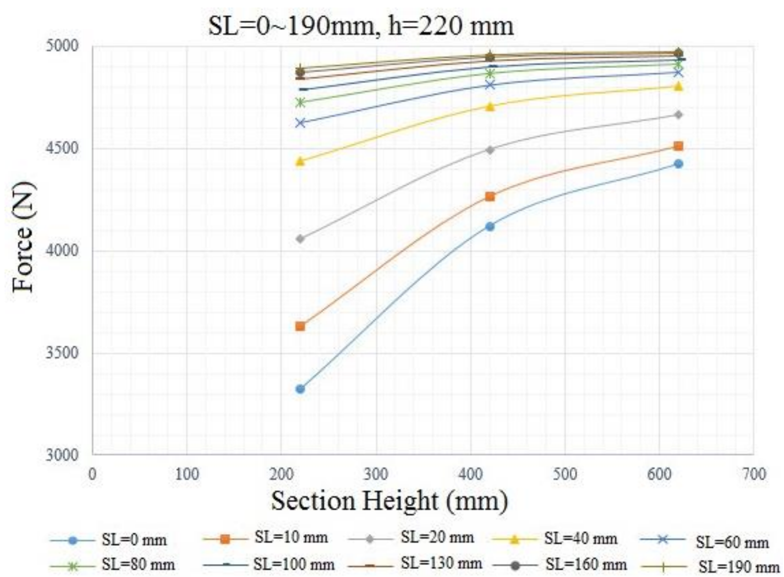


**Fig. 25.** Change of flange shear force from section total shear with change of beam section height for models Ba-3600-0 to Ba-3600-190 (a = 220, 420 and 620 mm)

It is noteworthy that the results are based on an elastic analysis and the bending moment capacity at inelastic behavior should be affected by other factors in addition to the slot length, such as the width-thickness ratio of the beam flange. But it is certain that due to the reduction of moment at the connection, the bending capacity of the beam comes later. The loss of existing moment at connection section due the slot performance for example for models B420-3600-c and B620-2400-c are presented in Table 5.

## EVALUATION THE EFFECT OF BEAM MATERIAL POISSON'S RATIO ON SHEAR FORCE IN WEB AND FLANGES

Existence of transverse strains and volume deformations at beam section in connection region and restraint of Poisson's effect create a considerable portion of additional shear force in flanges due to their large width. In order to investigation of this claim in this research, un-slotted model B220-2400-0 in ANSYS workbench software was modeled again with a Poisson's ratio equal to zero and vertical shear stress distribution and the force value in the flanges and web are obtained at this section. Basically, it is assumed that regardless of the effects of lateral strain (in terms of considering Poisson's ratio of materials equal to zero in the software) the effect of restraint due to lateral strain is reduced and thus the share of flanges from vertical shear stress is reduced and added to web share from this shear.

According to the result of software what is happening is exactly similar to this prediction. With comparing the model in which the Poisson's ratio is equal to 0.3 with the similar model in which the Poisson's ratio is equal to 0 concluded that the graph of vertical shear distribution in the model with Poisson's ratio equal to 0 is very similar to the results of classical assumption. The result of the comparison is presented in Figure 26. Similar to the discussion of vertical shear stress, the vertical shear force of web and flanges at connection section for the models with and without Poisson's effect is presented in Table 6 that the results are exactly similar to shear stress. Figures 27 and 28 present the Poisson's effect on shear stress distribution in beam web and flange in software for models B220-2400-0 $(\vartheta = 0.3)$ and B220-2400-0 $(\vartheta = 0)$.

**Table 5.** The decrease of existing moment at connection section due the slot performance for models B420-3600-c and B620-2400-c

| Model | Decrease percent of existing moment | Model | Decrease percent of existing moment |
|---|---|---|---|
| B420-3600-0 | 0.00 | B620-2400-0 | 0.00 |
| B420-3600-10 | 0.35 | B620-2400-10 | 0.78 |
| B420-3600-20 | 1.61 | B620-2400-20 | 2.76 |
| B420-3600-40 | 3.66 | B620-2400-40 | 6.02 |
| B420-3600-60 | 5.45 | B620-2400-60 | 8.90 |
| B420-3600-80 | 7.07 | B620-2400-80 | 11.53 |
| B420-3600-100 | 8.58 | B620-2400-100 | 13.99 |
| B420-3600-130 | 10.70 | B620-2400-130 | 17.43 |
| B420-3600-160 | 12.72 | B620-2400-160 | 20.69 |
| B420-3600-190 | 14.63 | B620-2400-190 | 23.78 |

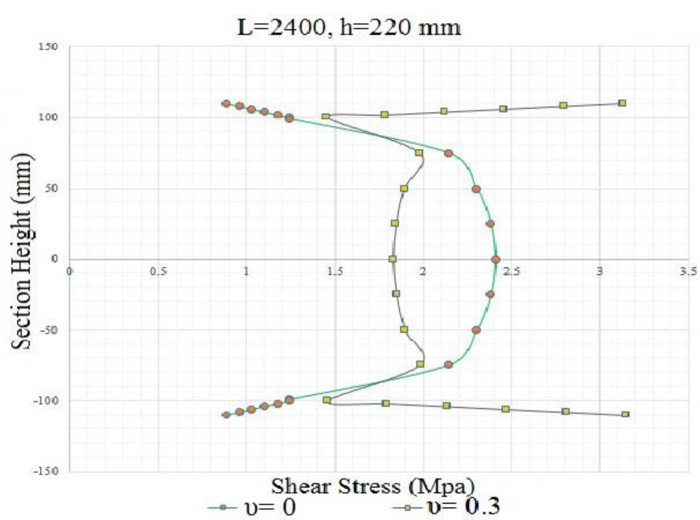


**Fig. 26.** Vertical shear distribution at connection section in the beam with transverse strains (ϑ=0.3) and without transverse strains (ϑ = 0) in model B220-2400-0

**Table 6.** Vertical shear force of web and flanges at connection section for model B220-2400-0 with and without Poisson's effect

| Model | Top flange force (N) | Web force (N) | Bottom flange force (N) |
|---|---|---|---|
| B220-2400-0 $\vartheta = 0$ | 295.12 | 4409.8 | 295.11 |
| B220-2400-0 $\vartheta = 0.3$ | 696.18 | 3611.5 | 692.35 |

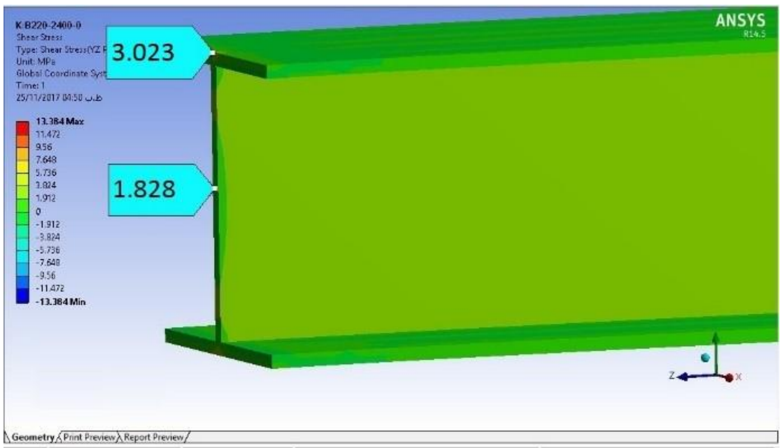


**Fig. 27.** Shear stress in model B220-2400-0, $\vartheta = 0.3$

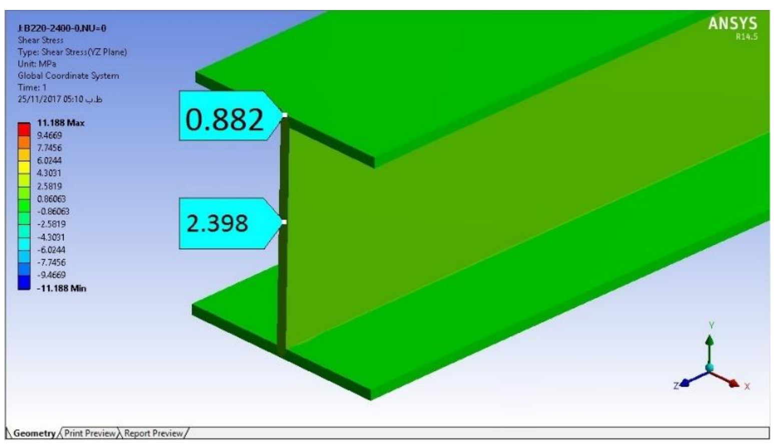


**Fig. 28.** Shear stress in model B220-2400-0, $\vartheta = 0$

## CONCLUSIONS

In this article at first evaluation of shear stress and shear force distribution at moment connection section was done in actual state in the form of linear static analysis using ANSYS Workbench finite element software. Then the obtained results were compared with the results of classical theory of shear stress and shear force distribution which are in the mechanics of materials. On the other hand another major purpose of this study is to assess the effect of slots with a width of 10mm and a maximum length of 190 mm between steel beam web and flanges junction on the force and shear stress distribution at moment connection in elastic range of material. All models were without buckling mode and were under concentrated load at top flange in mid span. For this purpose 120 beam finite element models with moment connections, in which parameters such as slot length, span length and section height were variable, were made for parametric study.

According to Finite Element study the results are far from the results of mechanics of materials and the major purpose was to correct the connection behavior by modeling the slots with limited length at moment connection. After each analysis, intended parameters and graphs were obtained. In summary the results of parametric study showed that:

- Beam flange at connection section has the ability to get even from 10 to 45 percent of the total shear forces of the section that are unlike the results of classical assumptions and relations of regulations.
- Increase in the slot length has a significant effect on decrease in the stress of outer fiber and increase in the stress of neutral axis especially in the initial length of slot and the results are coincided with the classical assumptions.
- Similar to discussion of the stress, what is seen in all models about the benefits of the slot performance is that creating slot and increasing of its length in all models lead to decreasing the portion of flanges from vertical shear force and increasing the portion of web from this shear. Accordingly equations of regulations, assuming the shear of flanges is low, are closed to reality.
- In models with the same section height and the same slot length the more the span length becomes great, the more the portion of flanges from shear force becomes great the portion of web from shear force becomes less.
- Increase of the portion of flanges and reduction of the portion of web from section total shear force by increasing the beam span length in models with lesser slot length is evident.
- In models with the same span length and the same slot length but with different section height as the section height becomes greater due to increasing the web height, flanges portion from section shear is diminished and on the contrary web portion will be greater.
- Similar to impact of beam span length at connection section shear reduction of the portion of web and increase of the portion of flanges from section total shear force by increasing the height of the beam, in models with lesser slot length is evident.
- The existence of slot in addition to improving the state of stress distribution and shear force distribution at connection section on other side leading to reducing the resisting moment at the connection section even up to 23 percent which is less than un-slotted state and certainly it is very suitable in the bending fractures.
- Regardless of the effects of lateral strain (in terms of considering Poisson's ratio of materials zero in the software) the effect of restraint due to lateral strain is reduced and thus the share of flanges from vertical shear stress is reduced and added to web share from this shear.
- According to mentioned advantages, nowadays slotted web beam to column connection can be used as a fantastic and simple idea to improve modern connections behavior. Undoubtedly, these great benefits are gained from the slot existence.

## REFERENCES


Abdollahzadeh, G.R. and Ghobadi, F. (2014). "Mathematical modeling of column-base connections under monotonic loading", *Civil Engineering Infrastructures Journal*, 47(2), 255-272.

Ahmed, S.R., Khan, M.R., Islam, K.M.S. and Uddin, M.W. (1998). "Investigation of stresses at the fixed end of deep cantilever beams", *Computers and Structures*, 69, 329-338.

AISC. (2016). *Specification for structural steel buildings*, American Institute of Steel Construction.

Beer, F.P., Johnston, E.R. and De Wolf, J. (2014). *Mechanics of materials*, 7th Edition, McGraw Hill Education.

Dow, J.O., Jones, M.S. and Harwood, S.A. (1990). "A new approach to boundary modeling for Finite

Difference applications in solid mechanics", *International Journal of Numerical Methods in Engineering*, 30, 99-113.

Dubina, D., Ciutina, A. and Stratan, A. (2001). "Cyclic tests of double-sided beam-to column joints", *Journal of Structural Engineering, ASCE*, 127(2), 129-136.

Durelli, A.J. and Ranganayakamma, B. (1989). "Parametric solution of stresses in beams", *Journal of Engineering Mechanics*, 115(2), 401.

FEMA. (2000). "Recommended seismic design criteria for new steel moment frame buildings", FEMA 350, Richmond (CA), SAC Joint Venture.

Goswami, R. and Murty, C. (2009). "Externally reinforced welded I-beam-to-box-column seismic connection", *Journal of Engineering Mechanics*, 136(1), 23-30.

Iwankiw, N.R. and Carter, C.J. (1996). "The dog bone: A new idea to chew on, Mod", *Modern Steel Construction*, AISC, 36(4), 18-23.

Jalali, S., Banazadeh, M., Abolmaali, A. and Tafakori E. (2012). "Probabilistic seismic demand assessment of steel moment frames with side-plate connections", *Scientia Iranica*, 19(1), 27-40.

Kang, C.H., Kim, Y.J.d., Shin, K.J. and Oh, Y.S. (2013). "Experimental investigation of composite moment connections with external stiffeners", *Advances in Structural Engineering*, 16(10), 1683-1700.

Kelly, P. (2013). *Solid mechanics, engineering solid mechanics*, The University of Auckland.

Lee, K.H., Goel, S.C. and Stojadinovic, B. (2000). "Boundary effects in steel moment connections", *Proceedings of 12th World Conference on Earthquake Engineering*, Auckland, New Zealand.

Lewei, T., Xuewei, H., Feng, Z. and Yiyi, C. (2016). "Experimental and numerical investigations on extremely-low-cycle fatigue fracture behavior of steel welded joints", *Journal of Constructional Steel Research*, 119, 98-112.

Maleki, S. and Tabbakhha, M. (2012). "Numerical study of slotted-web-reduced-flange moment connection", *Journal of Constructional Steel Research*, 69(1), 1-7.

Mahmoudi, M., Vatani, Oskouie A. and Havaran, A. (2013). "The effect of easy-going steel on KBF's seismic behavior", *Civil Engineering Infrastructures Journal*, 46(1), 81-94.

Miller, D.K. (1998). "Lessons learned from the Northridge earthquake", *Engineering Structures*, 20(4-6), 249-60.

Mohamad, A., Morshedi, M.A., Dolatshahi, K.M. and Maleki, Sh. (2017). "Double reduced beam section connection", *Journal of Constructional Steel Research*, 138, 283-297.

Nikoukalam, M. and Dolatshahi, K.M. (2015). "Development of structural shear fuse in moment resisting frames", *Journal of Constructional Steel Research*, 114, 349-361.

Rahman, M.Z., Ahmed, T. and Imtiaz, R.M. (2013). "Investigation of stresses in a beam with fixed connection using Finite Difference technique", *Global Journal of Researches in Engineering, Mechanical and Mechanics Engineering*, 13(2), Version 1.0, 7-15.

Ramirez, C.M., Lignos, D.G., Miranda, E. and Kolios, D. (2012). "Fragility functions for pre-Northridge welded steel moment-resisting beam-to-column connections", *Journal of Engineering Structures*, 45, 574-584.

Ricles, J.M., Sause, R., Garlock, M.M. and Zhao, C. (2001). "Post-tensioned seismic-resistant connections for steel frames", *Journal of Structural Engineering*, ASCE, 127(2), 113-121.

Timoshenko, S.P. and Goodier, J.N. (1979). *Theory of elasticity*, 3rd Edition, McGraw-Hill, New York.

Uddin, M.W. (1966). "Finite Difference solution of two-dimensional elastic problems with mixed boundary conditions", M.Sc. Thesis, Carleton University, Canada.

Valente, M., Castiglioni, C.A. and Kanyilmaz, A. (2017). "Numerical investigations of repairable dissipative bolted fuses for earthquake resistant composite steel frames", *Journal of Engineering Structure*, 131, 275-292.

Valente, M., Castiglioni, C.A. and Kanyilmaz, A. (2017). "Welded fuses for dissipative beam-to column connections of composite steel frames: Numerical analyses", *Journal of Constructional Steel Research*, 128, 498-511.

Vetr, M.Gh., Miri, M. and Ghaffari, F. (2012). "Seismic behavior of the Slotted Web (SW) connection on the Iranian I-shape profiles through experimental studies", *The Fifteenth World Conference on Earthquake Engineering*, Lisbon, Portugal.

Wilkinson, S., Hurdman, G. and Crowther, A. (2006). "A moment resisting connection for earthquake resistant structures", *Journal of Constructional Steel Research*, 62(3), 295-302.

Yu, Q.S.K., Uang, C.M. and Gross, J. (2000). "Seismic rehabilitation design of steel moment connection with welded haunch", *Journal of Earthquake Engineering and Structural Dynamics*, 126(1), 69-78.

Zirakian, T. (2008). "Lateral–distortional buckling of I-beams and the extrapolation techniques", *Journal of Constructional Steel Research*, 64, 1-11.