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Research Article

Effect of The Haunch Angle and Stiffener Types on Column-Beam Connection Behaviour Under Static Loading

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Load-Bearing capacity,
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Abstract

The strong column-weak beam principle, one of the earthquake resistant building design theories, require the connection area to be strong enough so that the plastic hinge forms in the beam. One of the proposed solutions is to strengthen the column-beam connection zone in steel connection with haunches. This study aims to look at parametrically behavior of column-beam haunched connections under the 100mm vertical displacement controlled loading using the finite element method. To obtain this, a total number of 21 finite elements model with 15, 30, and 45 degrees angles and 6 various stiffener types has been modeled by ABAQUS software. The research later discussed behavior of underlying components of haunch connections models such as the load-displacement curve, bearing capacity, extended end plate bending, stress distribution, and the position of the plastic hinge's development after finite element analysis. The study found that decrease in haunch angle improve the connection's bearing capacity, while in this case, the failure modes and plastic hinges will occur close to the joints which does not meet the code requirements. The article concludes that the 30-degree haunch angle is the most appropriate one in haunch connection and the three parallel and K-stiffeners is the most suitable reinforcement type for the haunched connections.

1. Introduction

Steel structures are among the demanding building types due to their high plasticity behavior in term of material properties and structural design requirements. The designs methods that are used in the column-beam connections influence the ability of the structures to withstand extreme plastic deformation and transformation. Prior to the 1994 Northridge and 1995 Kobe earthquakes, welded joints were commonly used in moment-resisting frames[1-4]. After the earthquakes, many cases of brittle fracture have been detected in welded joints [5-6]. The brittle fracture of the joints, which causes the sudden collapse of the structure, has increasingly brought attention and interest of designers in bolted connection types. Although bolted connection can be designed as rigid or semi-rigid with respect to welded connections, their initial stiffness relative to welded joints is lower[7-9].

In moment-resisting steel frames, one of the most crucial suggestions of the SCI and Eurocode 3 directives is to strengthen the connection area and make sure the plastic hinge occurs in the beam rather than the connection area. One of the methods for providing the conditions is to strengthen the joint area by using haunch sections in the lower flange of the beam.

Several studies have been carried out on the reinforcement of moment resisting connection before the Northridge earthquake. The studies indicated that the plastic hinge formed in the beam with the effect of the haunch on the lower flange of the beam and it was suitable for earthquake resistant structure design [10-15].

When the ductility level of a moment-resisting connection considered to be high (Montuori et al., 2017) [16], strengthening the connection area becomes crucial [7-8]. By increasing the strength of the beam in the connection area, haunch helps to design a more rigid connection and to determine the position of the plastic hinge. Reinforcing the connection area with a haunch ensures that the plastic hinge is formed at a far distance from the column or connections area, thus in the beam [11,17]. According to Eurocode 3 and SCI/BCSA, 1995 standards, the haunch angle in moment-resisting haunched connections is determined as a maximum of 45 degrees [8-9] . However, it is recommended that the haunch angle, should be within 30 ± 5 degrees in the AISC (2005)[18] , and can be extended to 50 degrees [19]. The column, which is the other element of the connection, is reinforced with stiffeners at the level of the beam flanges and in positions where intense forces such as hunched connections are transferred. Stiffeners should be used especially in haunched column-beam connections made to increase rigidity, play an active role in the plastic behavior of these connections. Various studies in the literature have discussed the effect of stiffening in the connections [17,20,21, 52-54]. Continuity plates (stiffeners) should be used to strengthen the column panel and it is recommended to place the upper and lower beam flanges[22]. Full-depth stiffeners in the beam flanges avoid local buckling of the beam flange and allow to occur outside the haunch length. In addition, experimental and analytical studies have shown that a T-shaped haunch with triangular geometry is the most effective type of haunches among the different shapes [23-24].

Another method that allows the plastic hinge to form in the beam is reducing the cross-section of the beams[25-28]. In this method, a weak region is created in the flanges of the beam, allowing the plastic hinge to form in this region[29]. Although both the moment-resisting haunched connections and the Reduced–Beam Section Connections (RBS) are in accordance to the strong column-weak beam principle, yet it was observed that the welded haunched connections performed better than the Reduced–Beam Section Connections (RBS)[27]. Haunched connections are also used between composite column-beam connections, which are very common in long span and high structures. Composite haunched connections acts similar to a rigid connection of column-beam connections. In addition, it has been

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found that haunch has positive effects on connection bearing capacity and exhibits a ductile moment-rotational behavior in column-beam connections [30-32].

Many studies have been conducted on the performance of haunched connections under the seismic applications and dynamic loads. studies showed that haunched connections consume 20% more energy than normal joints in cyclic horizontal loading. Moreover, haunched connections have proven to be a suitable solution for seismic applications with large plastic deformation demands [10-12, 33-34].

According to the seismic design regulations, the performance of column-beam connections must be proven by experimental tests (FEMA-355D) [35] in order to be able to analyze correctly . Nowadays, the finite element method has become a powerful tool used worldwide in most fields of engineering. Many studies have been conducted on steel connections and steel structures using finite element software [36-40, 47-51]. However, there are not enough studies in the literature about the haunch angle and the effectiveness of stiffening. In this study, the behavior of stiffening and moment-resisting haunched column-beam connections in different sizes and shapes, under the effect of monotonic vertical load is investigated using the ABAQUS/CAE program based on the finite element method. The first chapter of study explains a total of 21 finite element models developed to examine the column-beam connection type with three different haunch angles and seven different stiffnesses. It discusses the failure modes, load-displacement curves, plastic deformations of the joint for different haunch angles and emplacement shapes as well as angles of the stiffening plate comparation. Chapter two of the study focused on the modeling details about finite elements being studied. Chapter three gives data on the failure modes, load-displacement curves, and plastic deformations of the connections comparatively examined according to the obtained data. The last chapter concludes the topic, discuss the results and provide recommendations based on the analysis.

2. Numerical Studies

2.1. Generalities

In this study, the behavior of haunched column-beam connections under the monotonic vertical load has been investigated using the finite element method by ABAQUS/CAE [41] computer program. According to Eurocode 3 and SCI/BCSA , the haunch angle in moment-resisting haunched connections is determined as a maximum of 45 degrees [8-9]. Therefore, this study considers three different haunch angles of 15, 30, and 45 degrees with a total number of 21 connections, that are all reinforced with six different straight and diagonal stiffeners for each model.

2.1. Geometry of the Column-beam connections at Finite Element Modeling

In finite element method, a moment-resisting haunched connection has been modeled in accordance with the strong column – weak beam principle. Structural elements of HEA 140 for the column and IPE 140 for the beam were selected. The connection between the beam and the column has been established by bolting the welded extended end plate on the end of the beam to the column. The dimensions of the structural elements i.e., columns, beam sections and connections used in the study depicted in Figure 1 and the components of the numerical model illustrated in Figure 2. To transfer the maximum load to the column-beam connection, the beam length and the column height were chosen as 600mm and 2000mm respectively. The design of column-beam haunched connections was adopted from a previous study of haunch connection by the author (sadid, 2021) [42]. Table 1 contains all the details about the 21 models developed within the scope of the study.

The haunch sections depth was chosen equal to the beam depth for all models. The haunch length varies according to the angle, as shown in Figure 3. Due to large number of models, abbreviation has been used for each model. For example, the interpretation of the HA-45-3 model is as follows: HA stands for the haunch section, 45 indicates the haunch angle, and 3 stands the order of the model in that group. The description of each model is given below:

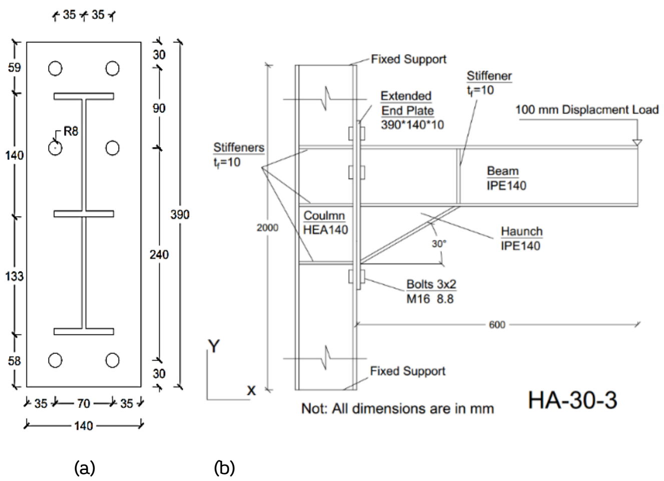


Figure 1. Geometrical Details of Models (a) Extended End Plate (b) Haunched Connection

Table 1. Details of the Haunched Connection Models

Model	Column	Beam	Haunch Section	Thickness (mm) Extended End Plate	Thickness (mm) Stiffener	No of Bolt	Bolt Diameter (mm)	Haunch Angle
HA-15-1	HEA140	IPE140	IPE140	10	10	6	16	15
HA-15-2	HEA140	IPE140	IPE140	10	10	6	16	15
HA-15-3	HEA140	IPE140	IPE140	10	10	6	16	15
HA-15-4	HEA140	IPE140	IPE200	10	10	6	16	15
HA-15-5	HEA140	IPE140	IPE200	10	10	6	16	15
HA-15-6	HEA140	IPE140	IPE200	10	10	6	16	15
HA-15-7	HEA140	IPE140	IPE140	10	10	6	16	15
HA-30-1	HEA140	IPE140	IPE140	10	10	6	16	30
HA-30-2	HEA140	IPE140	IPE140	10	10	6	16	30
HA-30-3	HEA140	IPE140	IPE200	10	10	6	16	30
HA-30-4	HEA140	IPE140	IPE200	10	10	6	16	30
HA-30-5	HEA140	IPE140	IPE200	10	10	6	16	30
HA-30-6	HEA140	IPE140	IPE140	10	10	6	16	30
HA-30-7	HEA140	IPE140	IPE140	10	10	6	16	30
HA-45-1	HEA140	IPE140	IPE140	10	10	6	16	45
HA-45-2	HEA140	IPE140	IPE200	10	10	6	16	45
HA-45-3	HEA140	IPE140	IPE200	10	10	6	16	45
HA-45-4	HEA140	IPE140	IPE200	10	10	6	16	45
HA-45-5	HEA140	IPE140	IPE140	10	10	6	16	45
HA-45-6	HEA140	IPE140	IPE140	10	10	6	16	45
HA-45-7	HEA140	IPE140	IPE140	10	10	6	16	45

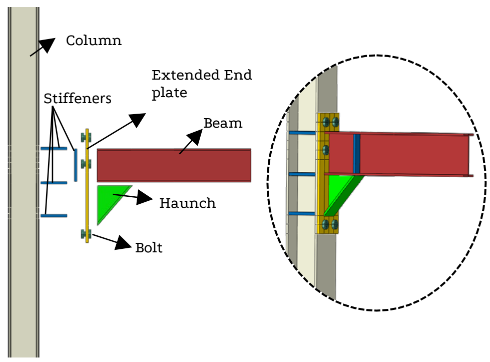


Figure 2. Finite Element Model of Haunched Connection

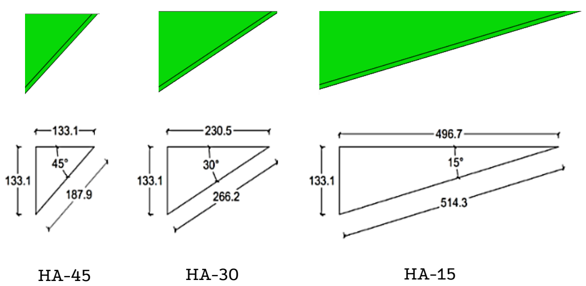
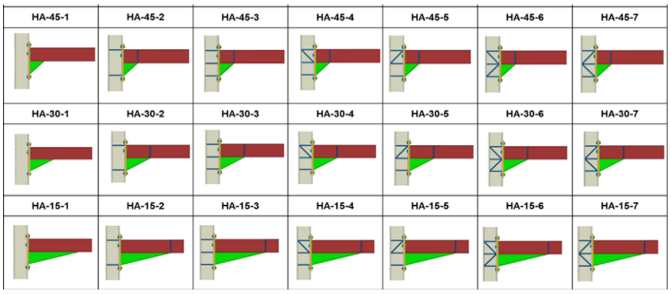


Figure 3. Dimensions of the Modeled Haunches

•HA-1 : Haunched Connection
•HA-2 : Double parallel Stiffened Haunch Connection
•HA-3 : Triple parallel Stiffened Haunch Connection
•HA-4 : Triple parallel Stiffened Haunch Connection with additional N stiffener
•HA-5 : Triple parallel Stiffened Haunch Connection with additional Inverted N stiffener
•HA-6 : Triple parallel Stiffened Haunch Connection with additional K stiffener
•HA-7 : Triple parallel Stiffened Haunch Connection with additional Inverted K stiffener

This study consists three 3 main groups of 15, 30, and 45 degrees of haunch angles for which stiffeners were placed in 6 different positions. In addition to 3 unstiffened reference models, a total number of 21 different types of haunch column-beam connections were created for the study. Details and schematic views of the finite element models of haunched connections with 15, 30, and 45 degree angles are given in Table 2.

Table 2. Finite Element Models



2.2. Material properties

One of the parameters that directly affect the results of finite element analysis is the material property defined in the software. The widely used PDM (Plasticity in Ductile Materials) model which represent the metal behavior is utilized in this study. The stress-strain curves of the PDM model are given in Figure 4. The elastoplastic stress-strain curve of the steel and bolt that was imported into the Abaqus software is presented in Figure 5a and 5b.

In finite element analysis, true stress-strain curves are used instead of engineering stress-strain curves. The engineering stress-strain curve can be transformed into the true stress-strain curve with the help of below equations [41,47,55] :

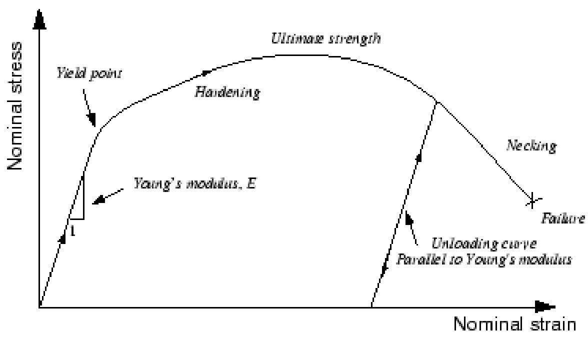


Figure 4. Plasticity in Ductile Material [41]

$$\sigma_T = \sigma_{nom}(l + \varepsilon_{nom}) \qquad \text{(Eq.1)}$$

$$\varepsilon_T = ln(l + \varepsilon_{nom}) \qquad \text{(Eq.2)}$$

In the above equations, σ_T stands for true stress, ε_T true strain, σ_{nom} engineering stress, and ε_{nom} donates the engineering strain.

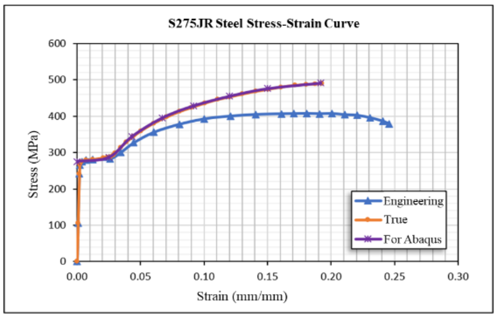
As the study focused on the numeric analysis of different models, some of the parameters for materials properties have been adopted from previous literature. The elastoplastic stress-strain relationship for the high strength bolts (Bull et al., 2015) [43] and for steel used in extended end plate, beam, column, and haunch (Nasery, 2019)[44] have been defined based on existing research. The material properties of the models defined in the ABAQUS software given below in Table 3 and the engineering and true stress – strain curves are depicted in figure 5a and 5b respectively.

Table 3. Material Properties

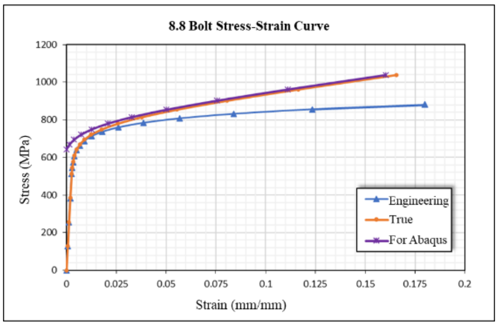
Material	Yield Stress (MPa)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Poisson Ratio	Plastic Strain
Steel	275	495	200	0.3	0.2
Bolt (8.8)	640	1040	200	0.3	0.15

2.3. Boundary Condition and Loading

To obtain an accurate result of the analysis, the software requires few boundary conditions while applying loads on the model. Figure 6 explains the boundary condition and loading of models in the software. The fixed supports selected at the ends of column by defining two kinematic connectors, one at each end of the column. Furthermore, to prevent any out-of-plane motions, a displacement boundary condition is applied on the beam that acts as lateral bracing.



(a)



(b)

Figure 5. Stress-Strain Curves; (a) S275JR Steel (b) M16 8.8 Bolt

Normal and tangential contact interactions have been defined between all elements. Normal contact conditions are created with the hard-contact feature that allows separation after contact. This hard contact has not allowed the slave nodes to enter the main surface in any way. For tangential behavior, a friction coefficient of 0.4 is defined depending on the contact surfaces [45] . The "Tie" command in Abaqus was used to model and simulate the welded elements. This feature allows structural elements to completely transfer the movement between the connected surfaces to each other.

In specified distance of 600mm, a loading point is defined at the end of the beam. To avoid local collapse at the loading point, all node points on the edge of the beam and column are connected to the reference point with the help of a kinematic connector.

In all analyses, using static loading a vertical displacement of 100mm has been considered at the end of the beam under loading. The values of reaction forces and displacements were obtained from supports at the end of the column and the loaded point of the beam end respectively, and the load-displacement curves were drawn. NLGEOM feature is activated to obtain geometric nonlinearity that may occur due to large plastic deformations. Loading has been applied in two steps. In the first step, a pretension standard load of 88kN was applied to the bolts as shown in Figure 6. In the second step, to examine the performance of the connection, loading was carried out under the vertical displacement of 100 mm applied to the beam end. Thus, both the pretension load and the vertical displacement load are included in the analyses.

2.4. Element Type and Mesh Sensitivity

As suggested by Ruffley (2011) [46], 3D solid elements were used to simulate the finite element models. As shown in Figure 7, C3D8R [47] (first order reduced integration continuous element), a six-edge solid element type that allows nonlinear geometric and material behavior, is used in all models [12,21]. Based on a study carried out for the finite element mesh sensitivity, the size of mesh for different elements determined as 10mm for endplate and column stiffeners, 5mm for bolts, 20mm for beam and haunch, 15mm for beam stiffeners, 10mm for column panel zone area, and an approximate mesh size of 100mm for places far from the connection. (Figure 7).

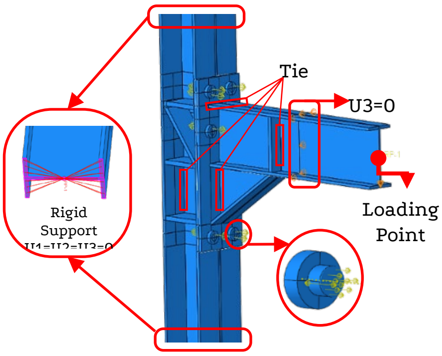


Figure 6. Finite Element Modeling, Boundary Conditions and Loading

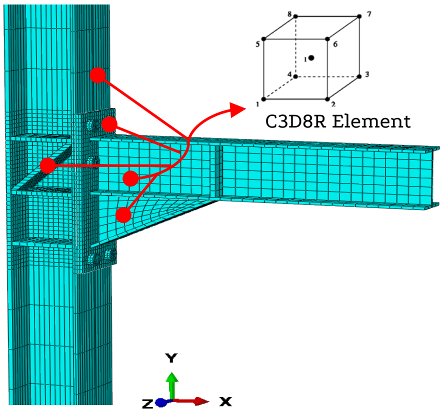


Figure 7. Finite Element Modeling, Mesh Sensitivity

2.5. Application and validation of proposed numerical method

A validation study was carried out to control the model and finite element type used in the study. For this purpose, the JD1 laboratory sample (Shi et al., 2007)[45] was remodeled and analyzed in the Abaqus program using the finite element method. In their study, Shi et al. (2007) [45] investigated the effects of the end plate and stiffeners on the column-beam connections in accordance with the moment-rotation capacity of connections. The result gained from finite element analysis and experimental study compared and revealed to be closely similar with each other. Comparative result of both studies has shown in figure 8 and 9.

As it is observed, the moment capacity and deformation of numeric model of the finite element are in good agreement with the experimental results. It was found that there is a 5% difference between the experimental (Shi et al., 2007) [45] and the validation studies, which is in an acceptable range.

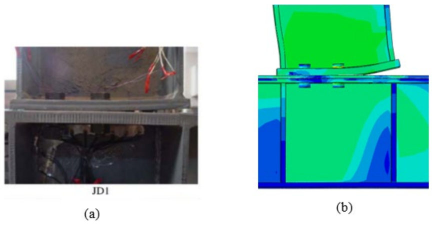


Figure 8. Model Analyzed by (a) JDI Laboratory Sample and (b) FEM

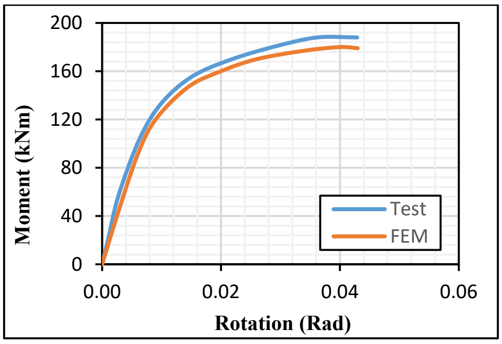


Figure 9. Comparison of Experimental and FEM Moment-Rotation Curves

3. Results and Discussion

In this chapter, the outputs of analysis i.e., Von Mises stresses, plastic deformations, and load-displacement curves were investigated. The performance of the models has been evaluated in terms of haunch angle, deformation capacity, effects of stiffeners, and strength.

Von Mises stress distributions and plastic deformations of the models with 15, 30, and 45 degrees haunch angle and different stiffening types are given in figure 10.

As a result of 100mm vertical displacement loading, bending and local buckling occurred in the extended end plate and column panel zone of the unstiffening models defined as the reference, as shown in figure 10.

It is seen that the bending of the extended end plates and the local buckling in the column panel zone decrease as the number of stiffeners increase.

It means that the number of stiffeners have a direct impact on the strengthening of the joint.

The welded are, column, haunch flange, and panel sections of the HA-15 models have experienced higher concentrations of stresses. It is predicted that collapse could happen in certain areas. On the flip side, in the HA-30 and HA-45 models, it is observed that the stresses are more concentrated outside the connection area. Therefore, it is concluded that in these models, failure may occur outside the connection area. As seen in Figure 11, in all 15 degree haunched connection models, plastic hinges occurred at the connections area, where the column flange is welded to the extended end plate. One of the reasons is that the 15-degree haunch section is more exposed and bear the majority of applied loads. In addition, in the 30 and 45-degree haunch models, the plastic hinge occurred in the beam outside the haunch length. This is the desired performance level according to the earthquake-resistant building design principle [7-9].

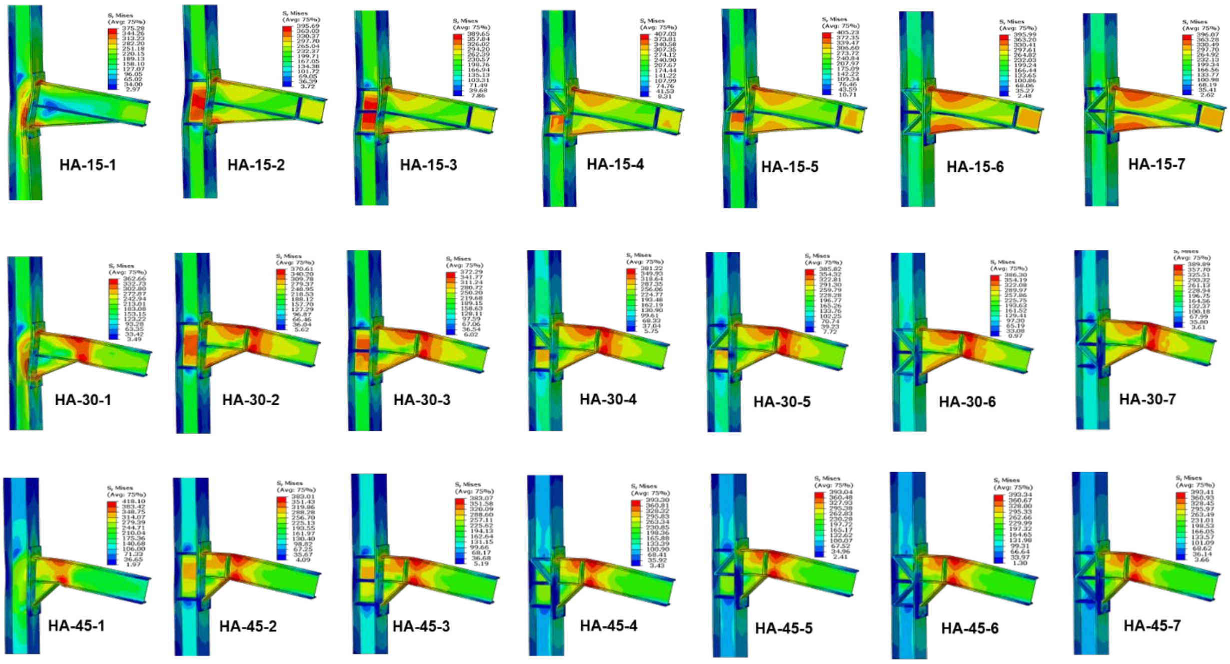


Figure 10. Von Mises Stress Distribution

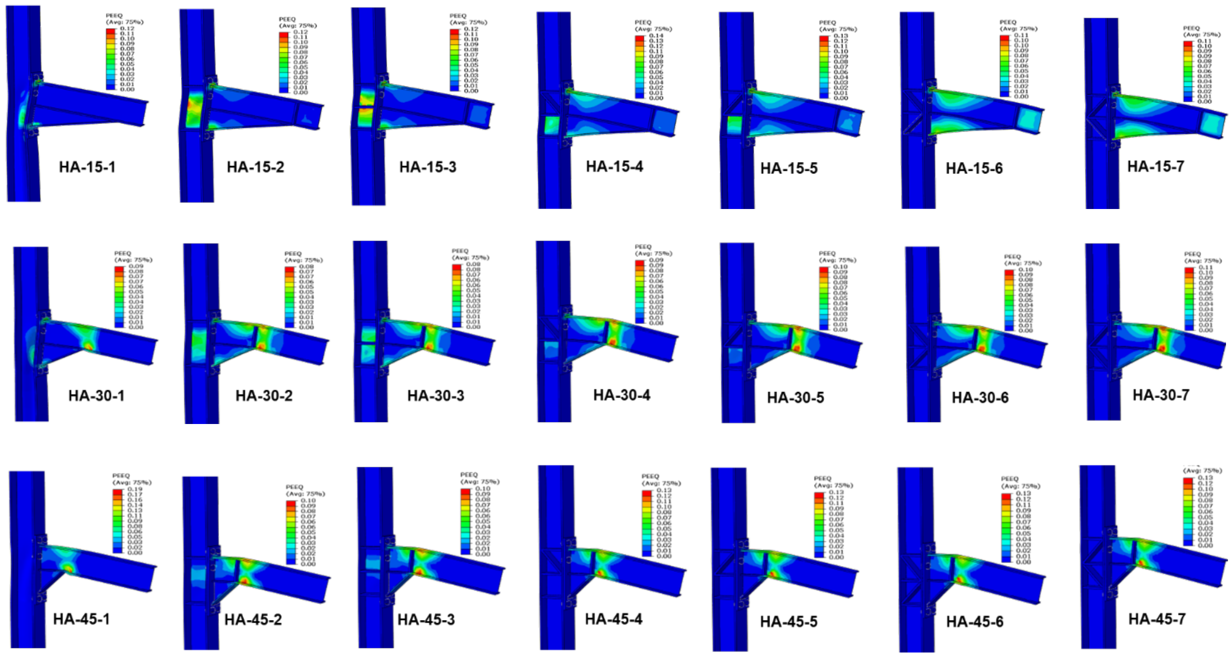
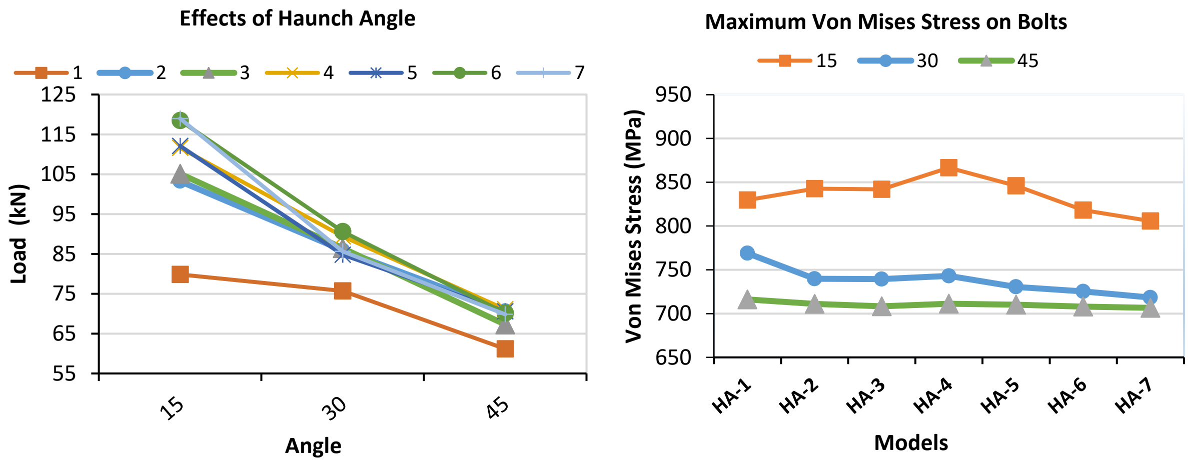


Figure 11. Plastic Deformations (PEEQ)



(a) (b)

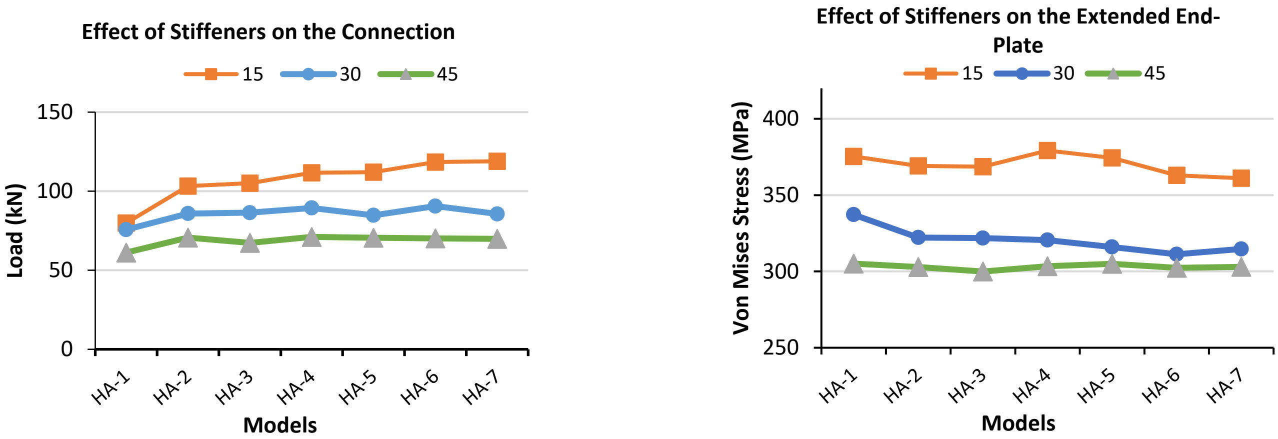
Figure 12. a) Effects of Haunch Angle, b) Maximum Von Mises Stress on Bolts

From figure 12, it is seen that by increasing the haunch angle from 15 to 45 degrees, the connections load bearing capacity is decreased. This decrease is approximately 25% and 40% in unstiffened and stiffened connections respectively (Figure 12. a). It shows the effectiveness of using stiffeners in order to prevent local buckling that will occur in the haunched column-beam connections, especially in the column panel zone. Bolts in 15 degree haunched connections with stiffeners are subjected to 13% more stress than 30 degree haunched connections, while they are subjected to 20% more stress than 45 degree haunched connections (Figure 12.b). For all stiffened and unstiffened connections, the smaller the haunch angle, the greater the stress on the bolts. It indicates the importance of bolts in haunched column-beam connection design.

In terms of stiffener effects, it was observed that Triple Parallel and K stiffener type is the most effective one among the used stiffener which considerably increased the load-bearing capacity of the connection (Figure 13.a).

As the stiffness of the connection increases, the effects of the change in the haunch angle on the load-bearing capacity are observed more clearly. Figure 13.b represent the effects of the change in the haunch angle on the extended end plates. İt was also found that the extended end plates have been subjected to less stress in the 45-degree haunched connections compared to the 15 degrees.

As seen in Figure 14, as the number of stiffeners increase, the extended end plates are subject to less stress, and the bearing capacity of the connection increases due to the strengthening of the panel zone. On the other hand, it is seen that as the haunch angle decreases, the amount of stress in the extended end plate, haunch section, and bolts increase. In addition, the extended end plates of 15-degree haunched connections made considerable deformations in all models, except for the K-stiffened model. Moreover, it is observed that there are negligible deformations in the extended end plates of the N and K stiffened models at the 30 and 45 degree haunched connections.



(a) (b)

Figure 13. a) Effect of Stiffeners on the Connection b) Effect of Stiffeners on the Extended End-Plate

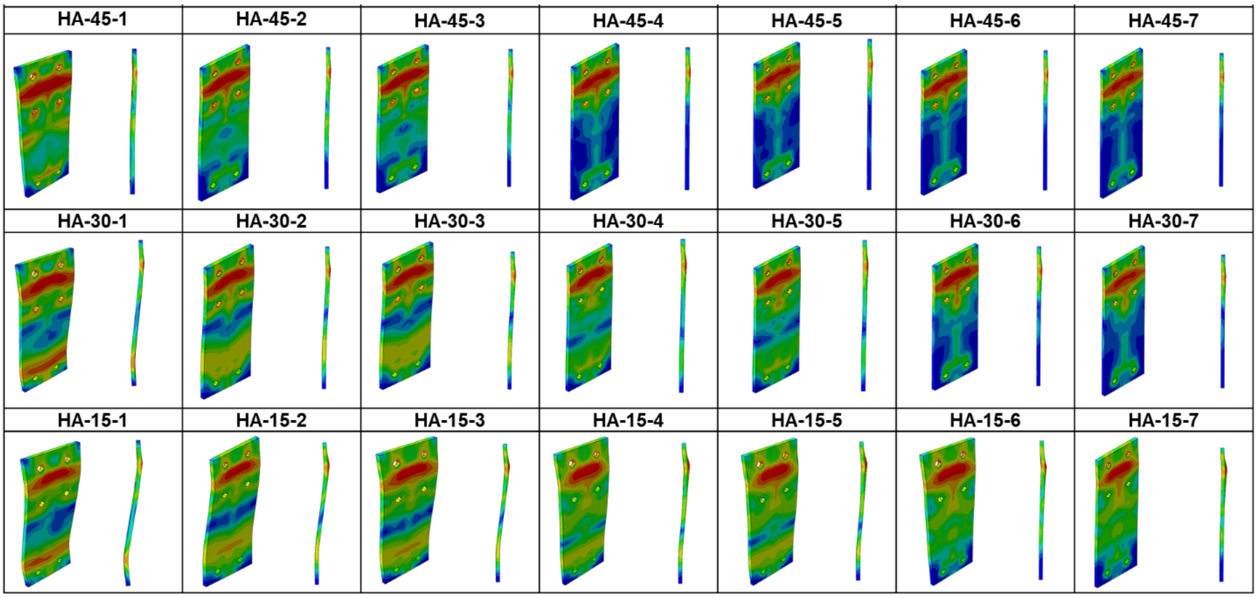


Figure 14. Stress Distribution at Extended end plates

In terms of occurred stress in haunch sections, it has been observed that the haunch section is actively exposed to stresses in the 30-degree haunched connection while in the 45-degree haunched connections, the N and K stiffeners and the beam section exposed to large stresses at the joints. In the meantime, the result shows that the haunch sections and the column transfer a large number of stresses to the connection in the 15-degree haunched connections (Figure 15). As shown in Table 4, since the stress values in the HA-4 and HA-5 models are higher than the other models, they can be defined as the models with the highest load bearing capacity among the 15, 30 and 45 degree models.

As it is seen in Figure 16, all stiffened haunched connections performed better behavior and higher load-bearing capacity than the reference HA-1, HA-2, and HA-3 unstiffened haunched connections. According to the data obtained, when the stiffened haunched connection models are compared with the unstiffened reference models, the 15-degree and 30-degree haunched connections exhibited a high load-bearing capacity rate of 27%-49%, 12%-18% respectively, and the 45-degree haunched connection showed high load-bearing capacity of 10%. In terms of the haunch angle, it was found that the models with a 15-degree haunch angle posed 22% and 48% more load-bearing capacity than the 30 and 45-degree haunched connection models respectively.

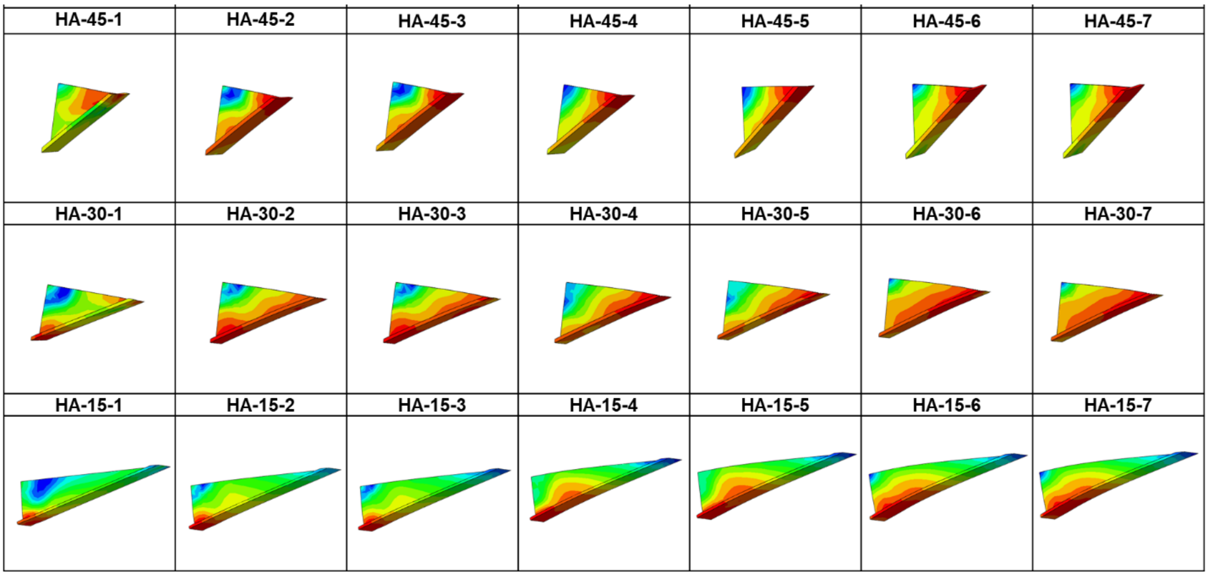


Figure 15. Stress Distribution at Haunches

Table 1. Analysis Results of Finite Element Models

Model	Haunch Angle	No of Stiffener	Max Load (kN)	Von Mises Stress (MPa)				Plastic Deformation PEEQ			
				Connection	Bolt	Extended end plate	Haunch	Connection	Bolt	Extended end plate	Haunch
HA-15-1	15	-	79.84	375.28	829.72	375.28	335.78	0.12	0.08	0.12	0.06
HA-15-2	15	2	103.22	395.69	842.7	369.17	360.58	0.12	0.08	0.12	0.07
HA-15-3	15	3	105.1	389.65	841.85	368.63	357.75	0.12	0.08	0.12	0.07
HA-15-4	15	4	111.62	407.03	866.62	379.2	341.71	0.14	0.1	0.14	0.05
HA-15-5	15	4	112.1	405.23	845.97	374.4	343	0.13	0.09	0.13	0.05
HA-15-6	15	5	118.47	395.99	818.24	362.91	365.54	0.11	0.07	0.11	0.08
HA-15-7	15	5	118.97	396.07	805.77	361.05	366.32	0.11	0.06	0.11	0.08
HA-30-1	30	-	75.69	362.66	768.91	337.17	320.54	0.09	0.04	0.07	0.03
HA-30-2	30	2	85.89	370.61	739.74	322.17	319.43	0.08	0.02	0.05	0.03
HA-30-3	30	3	86.44	372.29	739.4	321.8	318.9	0.08	0.02	0.05	0.03
HA-30-4	30	4	89.39	381.22	743	320.54	316.67	0.09	0.02	0.05	0.03
HA-30-5	30	4	84.77	385.82	730.47	316.03	318.18	0.1	0.02	0.04	0.03
HA-30-6	30	5	90.6	386.3	725.28	311.23	324.67	0.1	0.02	0.04	0.03
HA-30-7	30	5	85.64	389.89	718.36	314.72	321.07	0.11	0.01	0.03	0.03
HA-45-1	45	-	61.17	418.1	716.18	305.12	324.14	0.19	0.01	0.02	0.03
HA-45-2	45	2	70.68	383.01	711.02	302.86	304.32	0.10	0.01	0.03	0.02
HA-45-3	45	3	67.28	383.07	708.33	299.93	303.55	0.1	0.01	0.02	0.02
HA-45-4	45	4	71.1	393.3	711.32	303.37	306.41	0.13	0.01	0.02	0.02
HA-45-5	45	4	70.56	393.04	710.16	304.94	306.01	0.13	0.01	0.02	0.02
HA-45-6	45	5	70.16	393.34	707.9	302.34	307.46	0.13	0.01	0.02	0.02
HA-45-7	45	5	69.83	393.41	706.58	303.01	307.24	0.13	0.01	0.02	0.02

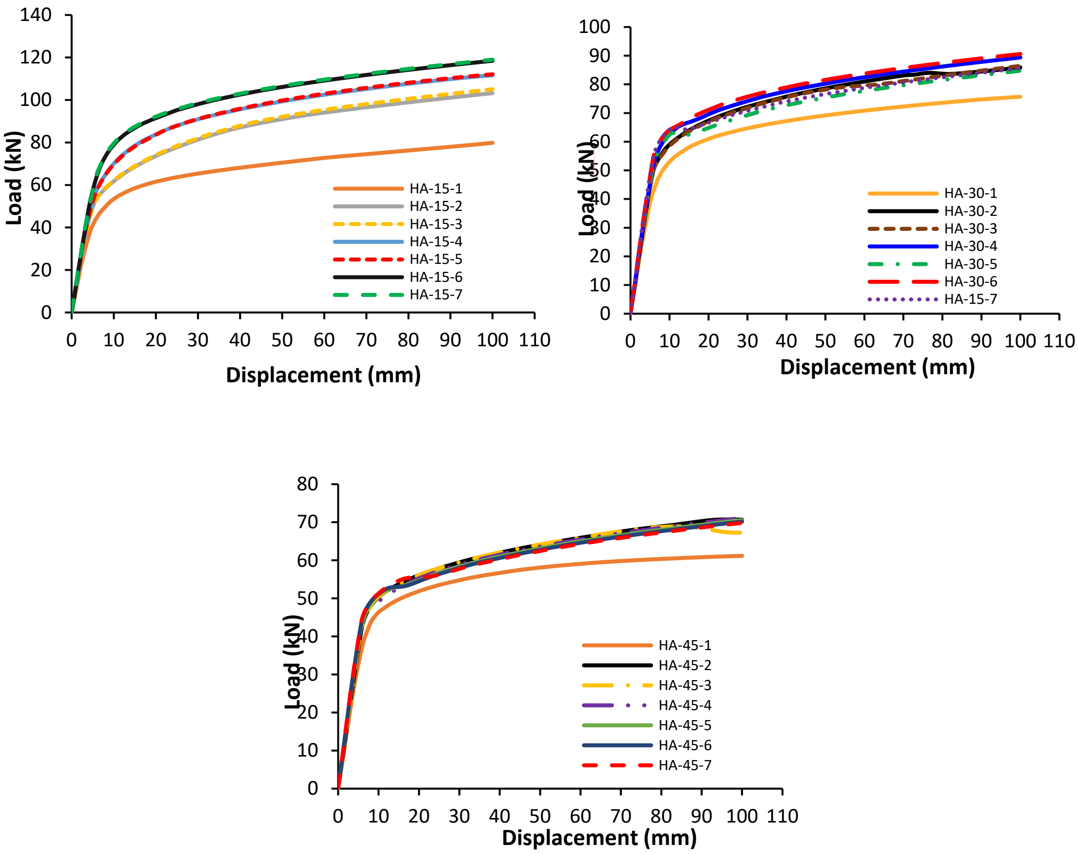


Figure 16. Load-Displacement Curves of Finite Element Models

4. Conclusions

This study aims to investigate parametrically the behavior of column-beam haunched connections under the monotonic vertical load using the finite element method. To fulfill this, a total number of 21 finite elements model including 3 reference unstiffened model and 18 stiffened finite element models pertaining to seven various types of column-beam connections with three different 15, 30, and 45-degree haunch angles as well as six different types of stiffeners that are used to strengthen the column-panel zone were developed. The research later discussed behavior of underlying components of haunch connections such as the load-displacement curve, bearing capacity, extended end plate bending, stress distribution, and the position of the plastic hinge's development as a result of the finite element analysis.

Following are the summary of significant findings and recommendations from this parametric study:

It has been observed that the connections load bearing capacity is indirectly depended on the haunch angle. As the haunch angle decrease from 45 to 15, the connection's bearing capacity increase. The model with a 15-degree haunch angle demonstrated 22% and 48% more load-bearing capacity than the 30 and 45-degree haunch models, respectively.

However, in this case, the failure modes and plastic hinges will occur close to the joints due to the higher stress concentration in these regions which does not meet the code requirements.

While in both 30 and 45-degree haunched connections the plastic hinge has formed at the beam – haunch intersection, the 30-degree haunched connections are carrying approximately 22% more load than the 45-degree haunched connections. Additionally, there is less stress and deformation in bolts and extended end plates in 30-degree haunches compared to the 15-degree haunches. Therefore, the 30-degree haunch alignment is defined as the most appropriate angle among the examined 15, 30, and 45-degree haunch angles.

Since the connection bears more load in 15 degree haunch position, so that the greatest stress and plastic deformations in the bolts occurred at a 15-degree haunched connections. Therefore, it is recommended to use larger bolts in low angle haunched connections.

It was revealed that reduction of haunch angle from 45 degrees to 15 degrees has significantly strengthened the haunch section (beam and haunch section together) and experienced more load. Due to this situation, a large deformation occurs at the extended end plate, and it reaches its yield strength. To prevent this occurrence, it is recommended to choose thicker extended end plates for haunched connections below 30 degrees.

It has also been noticed that the installed stiffeners on the column panel zone prevent the bending and buckling of the extended end plate and the column panel zone, respectively.

Finally, the type of stiffeners has also contributed to the load bearing capacity of haunched connections. Among the 6 different stiffening types used to strengthen the panel zones and prevent buckling, the three parallel and K-stiffened haunched connection types with 15, 30, and 45 degrees carry 50%, 12% and 10% more load compared to the 15,30 and 45 degree unstiffened reference haunched connection model, respectively. The study suggests that three parallel with K–Stiffeners is the most suitable reinforcement type for the haunched connections.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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