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Investigating of the effect of composite and welded connections on the cyclic behavior of steel bridges

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Abstract. Connections play a significant role on the seismic performance of structures subjected to gravity and lateral loads. One of the most important strategies for plastic hinge transfer is the strengthening of connections. Composite and welded connections are commonly used in steel bridges. Each of these connections can affect the structural response to lateral loads such as cyclic loads. In this study, four steel bridge models with different types of connections, including composite and welded connections, are created in the finite element (FE) platform ABAQUS. After validation of a FE model using available experimental data, cyclic loading has been employed according to the load history proposed by Scientific Advisory Committee (SAC). The results indicate that using composite connections can increase shear capacity and improve ductility of the system. Also using composite connection can transfer stress concentrated from connection to other areas.

Keywords: composite connection; dissipated energy; hysteretic curve; steel bridges; weld connection

1. Introduction

In recent years, experimental and analytical studies have been conducted on the behavior of connections in steel structure. Although steel bridges were designed in the past according to the seismic provisions of design codes, the criteria for the formation of plastic hinges and their propagation were not considered. Fractures of steel moment connections during the Northridge earthquake indicated that ductility in these connections should be increased. The main purpose of research studies after the Northridge earthquake was to transfer the plastic hinges from the joint region, such that the removal of the plastic hinges from the connection areas reduced the stress concentration and strain in the weld region, thereby reducing the amount of welding cracking and also preventing the brittle failure on the connection. Composite connection is one of these types of joints, in which the connection zone is strengthened by steel cover filled with concrete. In composite connection, the bridge pier is embedded in a compound area inside a cylindrical vessel that is welded to the superstructure. In this connection, the superstructure has no contact with the pier, and the

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contact force is transmitted through the steel cover. Since Iran is located in a high seismic zone, the occurrence of various earthquakes and their destructive effects are inevitable and thus, the necessity of repair and retrofit of structures with regard to heavy costs of rebuilding structures and downtime is indisputable. Bridges are one of the most important lifeline structures since the loss of functionality of the network system is directly related to the social and economic losses experienced after an earthquake. Therefore, accurate evaluation of their safety during seismic events is necessary (Baloevic *et al*. 2016, Mirzagoltabar Roshan *et al*. 2018, Pahlavan *et al*. 2017, Correia *et al*. 2017, Pahlavan *et al* 2019, Naseri *et al*. 2020a, Naseri *et al*. 2020b). Investigation of the seismic design code provisions of bridges shows that most of them have been presented based on linear methods and the use of nonlinear methods is recommended. However, the role of the superstructure to pier connection in the steel bridges with the moment resisting connection subjected to earthquake loading is vital. Failure of the connection, even if other components remain undamaged, will cause local or global failure of the structure. Therefore, to maintain the integrity of the structure, the connection system should be the strongest link in the structural stability chain.

Nakamura *et al*. (2002) studied the composite bridges in which the models had a steel superstructure and concrete pier. Bruneau *et al*. (2002) examined dissipated energy in the steel bridge structures. They compared performance of two steel bridges with eccentrically braced frames as the diaphragm system with horizontal and vertical eccentricity. Shaker *et al*. (2019) studied on responses of a concrete bridge with different deck-to-pier connections. They conducted a parametric study to investigate the different bearing types and pier height effects

Yang *et al*. (2015) investigated failure and cracking at the pier of concrete bridges under cyclic loading. Paolacci (2018) studied on the cyclic behavior of new pier-to-deck connections for short-medium span composite i-girder bridges. Stephens *et al*. (2015) studied on concrete-filled tube bridge pier connections for accelerated bridge construction. Results of their study showed that the three connection types provide excellent ductility under reversed-cyclic loading while all super-structure elements remained essentially elastic. The report provides design expressions, a design example and proposed codified language to facilitate immediate implementation of the research results into practice. Gheitasi *et al*. (2014) examined the numerical investigation of the capacity of bridges with concrete superstructures and steel pier using ABAQUS software. Fulmer *et al*. (2015) compared a bridge with steel superstructure and pier with and without composite connection. Their study showed that the use of composite connection increases its shear capacity. Palermo el al. (2007) presented design, modeling, and experimental response of seismic resistant bridge piers with posttensioned dissipating connections. Celik (2009) evaluated the behavior of diaphragms with buckling restrained braces in straight steel bridges. Results in this research indicated that the use of this type of brace improves the performance of the steel bridge. Hung *et al*. (2017) presented experimental study and numerical simulation of precast segmental bridge columns with semi-rigid pier connections

Mehrsorush *et al*. (2016) studied on cyclic response of precast bridge piers with novel column-base pipe pins and pocket cap beam connections. Fahmy *et al*. (2010) studied the effect of FRP on the concrete piers. In this study, they examined the length of the retrofitted region with FRP. Lotfollahi Yaghin *et al*. (2013) studied the retrofitting of I-shaped beams by steel plates in concrete bridges. The purpose of his research was to retrofit the 27 meter concrete beams constructed for a reinforced concrete bridge using ABAQUS software. Six different retrofitted specimens were used to investigate the behavior of wide and deep beams. In all specimens, reinforcement ratio was constant. Comparison of the different specimens under distributed static load showed that retrofit can increase the ultimate strength of the bridge from about 20% to 24.1%. They also proposed an ideal model for retrofitting and modeling these types of concrete beams. Afshin *et al*. (2012) investigated the behavior of the reinforced concrete columns retrofitted by rectified steel jackets. This study showed that the use of stiffeners for reinforcement of square steel jacket increases ductility and flexural strength and the retrofitted column can withstand more cycles of displacement without deterioration.

2. Finite element modeling

Finite element method by ABAQUS (2012) Software has been used to model the composite connection (steel and concrete). In all models, span length and height of pier is respectively 4.5 and 5 meters. Piers consist of steel cylinder with 205 mm in diameter and 15 mm in thickness, and the beams are of double I-shaped section. Specifications of different models are presented in Table 1.

Table 1 Specifications of the examined models

Model	The diameter of pier section (mm)	The thickness of the pier section (mm)	Composite diameter (mm)	Composite thicknes (mm)	Composite length (mm)
WB	205	15	305	15	-
CB-300	205	15	305	15	300
CB-400	205	15	305	15	400
CB-500	205	15	305	15	500
CB-584	205	15	305	15	584

All studs are modeled using a first-order and three-dimensional beam element called B31. Characteristics of the beam element are defined using the predefined sections of the ABAQUS software. Filler concrete is modeled using brick element with reduced integration C3D8R. This element has eight nodes and each node has 3 degrees of transitional freedom. The S4R element is used in modeling the superstructure and the pier. The S4R element is a four-node shell element and six degrees of freedom, including three degrees of transitions and three degrees of rotation per node. The bending and membrane function is predefined in the ABAQUS software. Then the beam and shell elements are connected to each other by using a Tie constraint method in a way that has composite behavior. Details of the contact between the steel and the concrete with the stud have been presented in (Rahnavard *et al*. 2016, Rahnavard *et al*. 2017, Venture 1999).

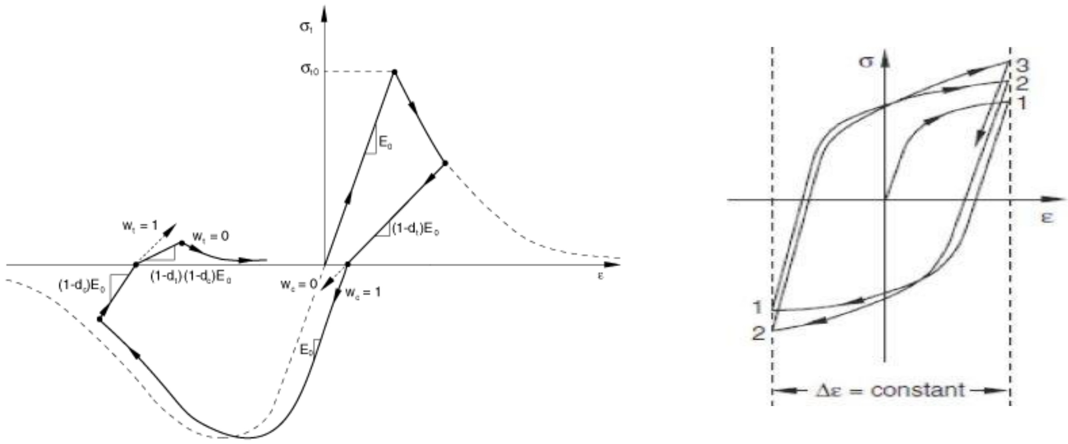
The model's properties include non-linear properties of materials, non-linear geometric behavior and nonlinear analysis. The nonlinear properties of materials have been used to model all steel components. The nonlinear property of materials in ABAQUS requires the actual stress corresponding to the plastic strain from the stress-strain engineering relationship. The behavior of materials is linear until yield stress. After that, they enter the strain hardening phase to reach the ultimate stress. The density of the members should be defined when the model is subjected to the dynamic analysis. Mass density of steel and concrete is assumed to be 7850 and 2400 kg/m^3, respectively. Yang's modulus for steel and concrete is 2.1×10^5 and 2.1×10^4 N/mm^2, and the Poisson coefficient is 0.3. In this study, ST37 steel was used for the pier and steel cover and superstructure. In order for modeling the concrete material, the damage plasticity model was used. Nonlinear behavior of concrete is presented using the isotropic damaged elasticity with isotropic tensile and

Table 2 Mechanical properties of concrete materials

Concrete	Yang's modulus (MPa)	Crack angle	Exit center	Viscosity parameter	Concrete tensile stress (MPa)	Concrete compressive stress (MPa)
fc28	21000	31	0.1	0.001	28	1.68

Table 3 Mechanical properties of steel materials

Steel name	Yang's modulus (MPa)	Submission Tension (MPa)	Ultimate tension (MPa)	Ultimate Strain
ASTM A500 Gr.B	210000	317	428	0.25
ASTM A572 Gr.50	210000	345	450	0.20

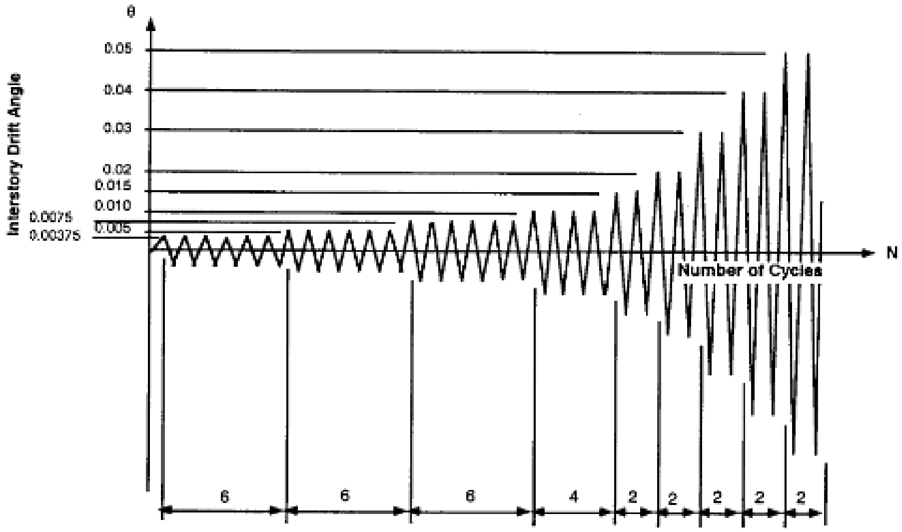


(a) (b)

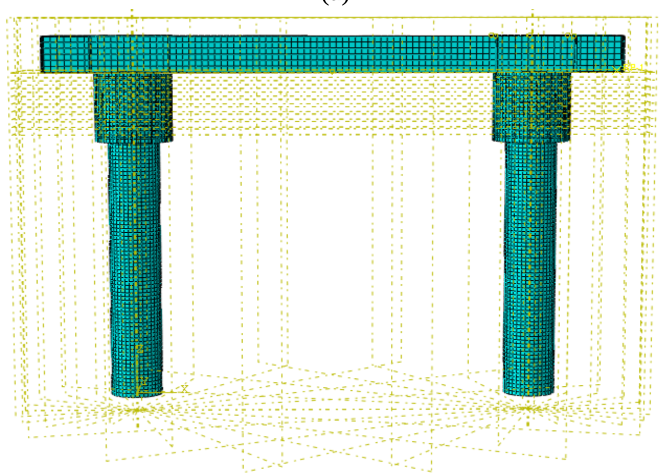
Fig. 1 Cycle behavior (a) concrete (b) steel

compressive plasticity. The nominal compressive strength of the concrete was 28 MPa. The compression curve is taken from ordinary concrete. The tensile strength is conservatively assumed to be 5.6% of the maximum compressive stress (Rahnavard *et al*. 2016). After the tensile cracks, the stress-strain relationship in the tension is reduced due to the transfer of the load to the bars. Also, the tensile resistance of the concrete is not considered after the cracking. The mechanical properties of concrete and steel materials have been summarized in Tables 2 and 3, respectively. Fig. 1 shows the cyclic behavior of concrete and steel.

In this study, to define the boundary conditions, the ends of both piers are pinned. The loading is applied as a displacement control load on the two ends of the beam. In this study, the cyclic loading pattern *SAC* (Sharifi 2005) was selected for all models. The Scientific Advisory Committee (SAC) is an advisory panel of independent scientific experts from Europe and Africa. It is the main advisory body to the General Assembly and the Secretariat. In this research, the cyclic analysis method presented by this committee has been used. The SAC standard, like some standards, provides a cyclic loading pattern that is used as a method in cyclic analysis. The cyclic loading protocol provided by the SAC is shown in the Fig. 2(a). For cyclic analyzes that most closely resemble seismic loads, the SAC protocol has been used. The structures of this research have been subjected to the Sec cycle cyclic load pattern and the structural responses have been extracted and



(a)



(b)

Fig. 2 (a) Cyclic curve of SAC, (b) Numerical model in ABAQUS

discussed. The size of the mesh was determined in such a way that the software can calculate the appropriate response. Fig. 2(b) illustrates the numerical model based on the experimental specimen (Fulmer 2015).

In many numerical studies based on laboratory results, the element in question is usually modeled with boundary conditions. Numerical analysis in Abacus software is very slow. Modeling the whole structure, in addition to being time consuming, takes a lot of time to analyze. But by creating a safe boundary condition that can influence the other parts of the structure on the desired element, sufficient accuracy can be achieved. This is a common method in numerical analysis. For example, Hug *et al*. conducted a similar study. They also created a numerical model and performed cyclic analysis while maintaining proper boundary conditions. Finally, they generalized the behavior of the element to the behavior of the structure.

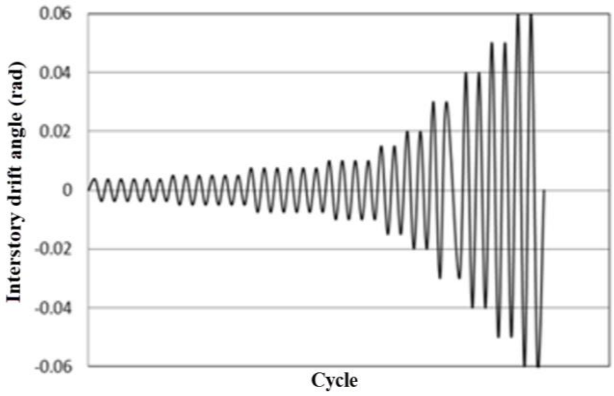


Fig. 3 Cyclic loading pattern (Fulmer *et al*. 2015)

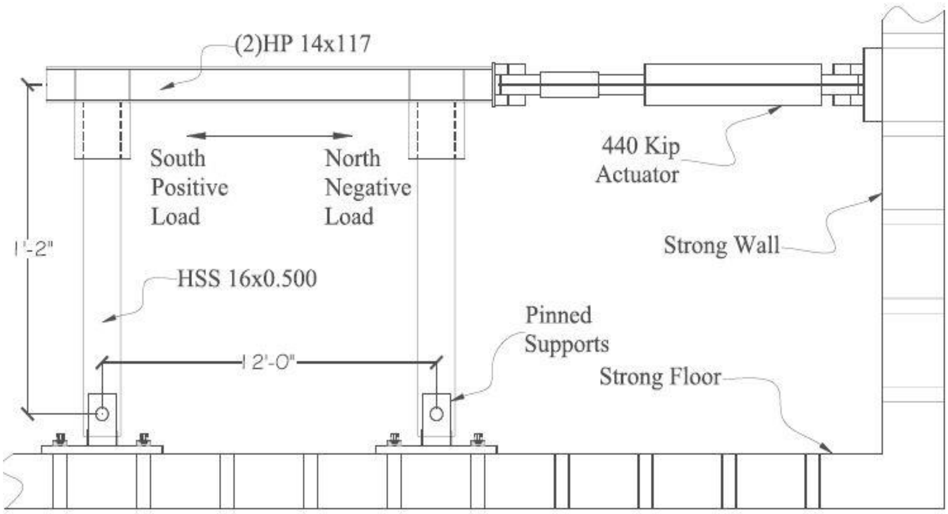


Fig. 4 Dimensions of the specimen tested by Fulmer *et al*. (2015)

3. Validation of finite element model in ABAQUS

The finite element method is an appropriate method for examining composite connections, which can be used to examine a variety of models under cyclic loading (Fig. 3). Therefore, in order to verify the models in this study, an experimental test reported by Fulmer *et al*. (2015) was modeled on ABAQUS. Dimensions and details of specimen have been shown in Figs. 4 and 5. The superstructure and pier sections are respectively 2HP 14X117 and HSS16X0.5.

For the proposed model, the ends of the piers are fixed. The properties of the concrete and steel materials are defined based on an experimental model as described in the previous section. A nonlinear static analysis is used to analyze the model. In Fig. 6, the analysis and experimental results have been shown in terms of the shear force versus lateral displacement. As can be seen, the maximum shear force obtained for the experimental specimen and the numerical model is respectively 647 and 626 kN. It can be seen in Fig. 6 that the strength deterioration for the numerical and experimental model has occurred at a rotation equal to about 200 mm. There is a good agreement

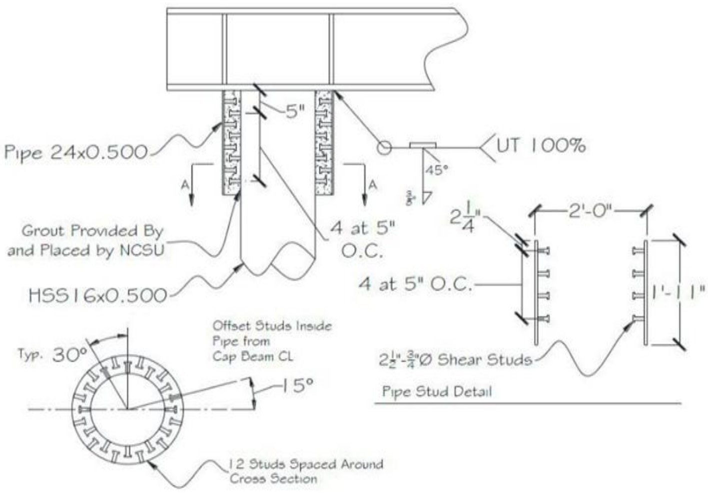


Fig. 5 Details of the specimen tested by Fulmer *et al*. (2015)

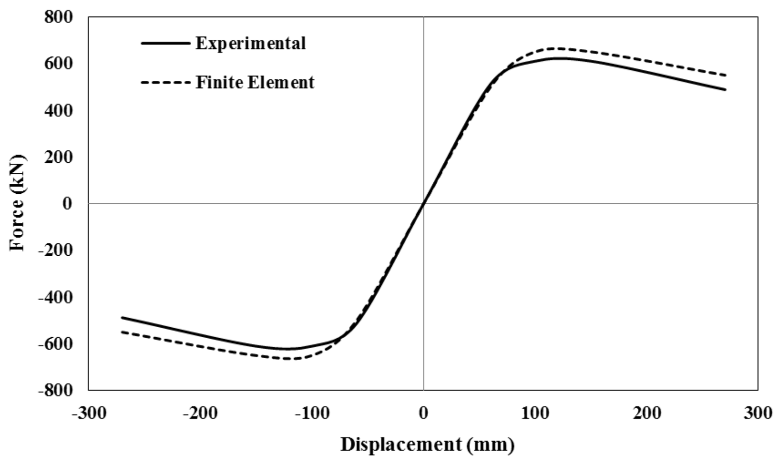


Fig. 6 Comparison of analytical and experimental results

between the numerical and experimental results in terms of their monotonic behavior which indicates the finite element model (FE model) is accurate. The deformation of the finite element and experimental model has been shown in Figs. 7 and 8, respectively. It can be seen that the buckling area of the bridge base occurs for both models under the composite region. Therefore, this model has sufficient accuracy, and the results can be used as reliable output.

4. Results

In this section, the performance of a steel bridge system with and without composite connections has been investigated in terms of cyclic hysteretic curve, dissipated energy, buckling, stress concentration and plastic hinges. In this study, the effect of length of the composite region on behavior of the system has also been evaluated which in previous studies was not considered.

Fig. 7 Deformed shape of the experimental specimen (Fulmer *et al*. 2015)

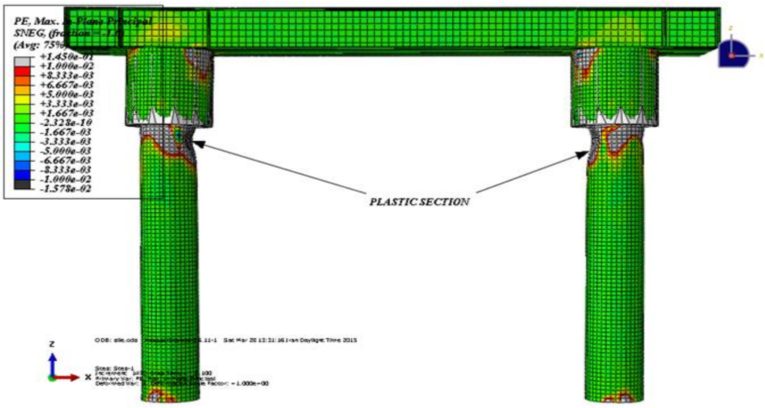


Fig. 8 Deformed shape of the numerical model

Fig. 9(a) illustrates the hysteretic curve for a steel bridge with a direct weld connection to a superstructure subjected to cyclic loading affect (WB). It can be observed that the stiffness increases until a displacement of 100 mm, then the slope of the increase in stiffness decreases. It can also be seen that the frame response is symmetric in both loading directions. The load carrying capacity of the steel frame is 410 kN. Also, the force corresponding to the formation of the first plastic hinge is 200 kN. Fig. 9(b) to 9(e) shows the hysteretic behavior of different composite steel bridge models. The load carrying capacity of the frame with a composite length of 300, 400, 500 and 584 is 545, 595, 624, and 640 kN, respectively. The results indicate that the use of composite connections increases the shear capacity of the steel bridge frame by 30%. The shear capacity also increases by extending the length of the composite region. Comparison of the models included composite connections shows that when the length of the composite area increases from 400 mm to 500 mm, 3% is added to the shear capacity. When the length of the composite region changes from 300 to 584, the shear capacity increases by 15%.

Fig. 10 shows the tension contour distribution for all models in a steady state. As shown in Fig.

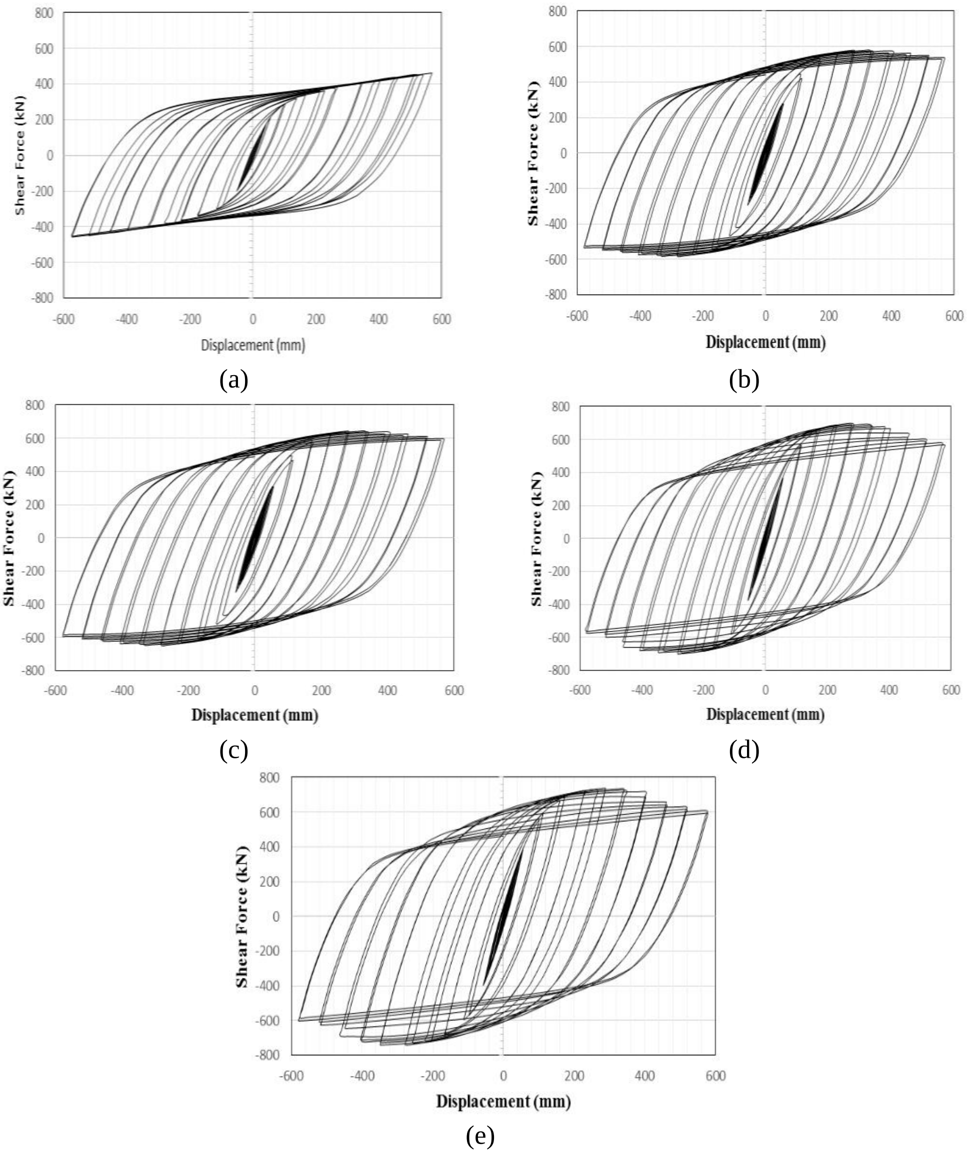


Fig. 9 Hysteretic curve (a) WB (b) CB-300 (c) CB-400 (d) CB-500 (e) CB-584

10(a), the maximum stress occurs in the connection joint of the superstructure to the pier and a large part of the stress in the model is found to be in this region. Fig. 10(b) to 10(e) show the stress distribution in various composite connections in steel bridge models. It can be observed that the composite connection removes the stress concentration from the bending region and distributes it throughout the model. In Fig. 10(d) and 10(e), it can be seen that the stress concentration is fully located in the pier. Also in the composite connection models of pier to superstructure, it can be concluded that the longer the composite length is the lower stress concentration on the connection area.

Fig. 11(a) shows the contour distribution of the plastic strain for the steel bridge model by direct

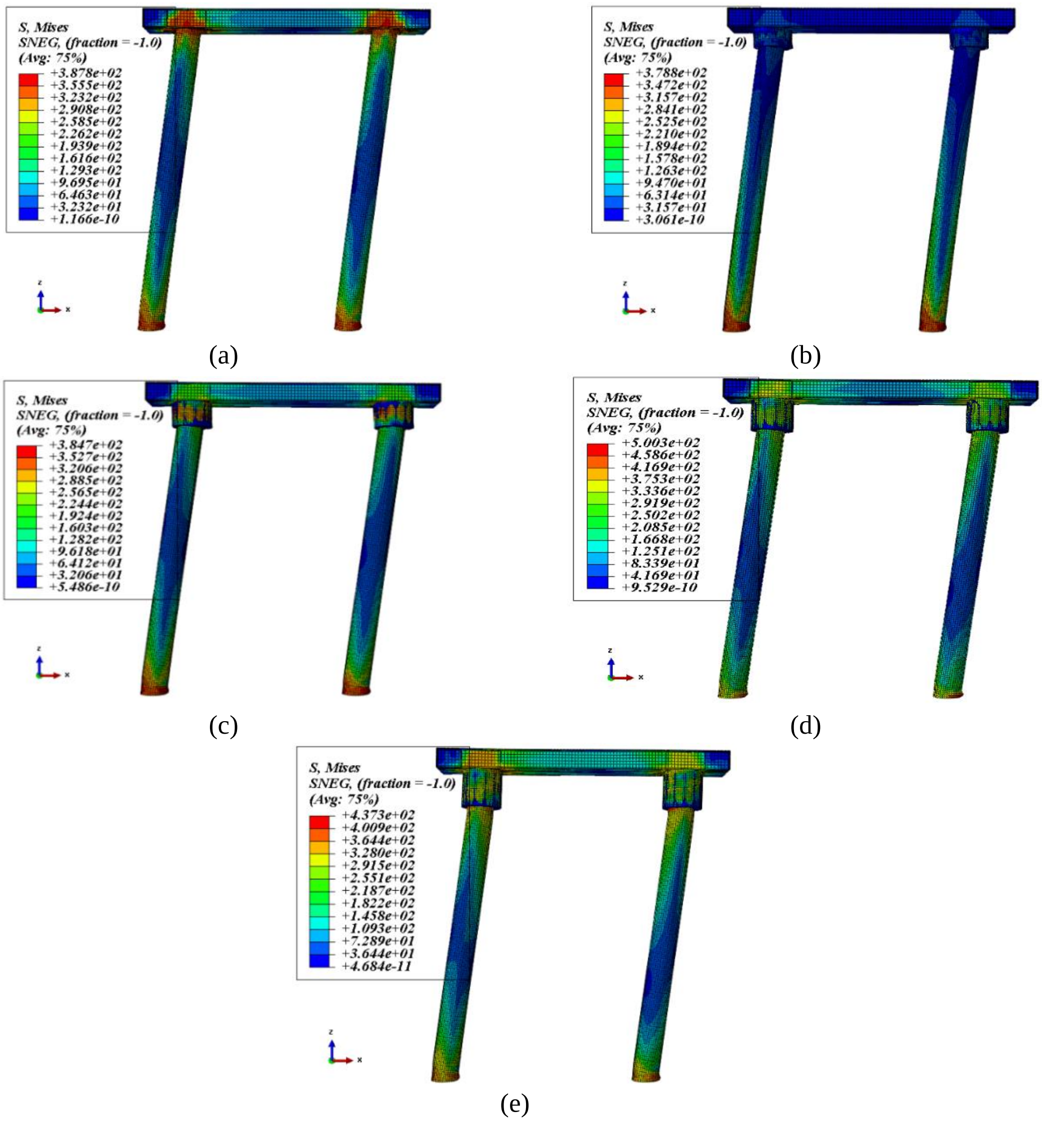


Fig. 10 Tension contour (a) WB (b) CB-300 (c) CB-400 (d) CB-500 (e) 584-CB

connection between pier and superstructure. As illustrated in Fig. 11(a), the most of plasticity occurs in the joint location of pier to the superstructure. Finally, the plastic hinge is formed in this region. Fig. 11(b) shows the contour distribution of the plastic strain for the composite connection of a steel bridge (CB-300) model with 300 mm length. As shown in Fig. 11(b), most of the plasticity is located on the cover plate within the vicinity of the superstructure and in the pier. Fig. 11(c) shows a plasticity trend similar to the CB-300 model (i.e., plasticity on the cover plate and in the pier); however the plasticity area in a 400 mm composite connection (CB-400) is smaller. Fig. 11(d) and 11(e), show the plasticity of a composite connection of a steel bridge model with 500-and 584-mm length (CB-500 and CB-584), respectively. As illustrated in these figures, most of the plasticity is removed from the joint location and occurs in the pier. In general, it is seen that using a composite

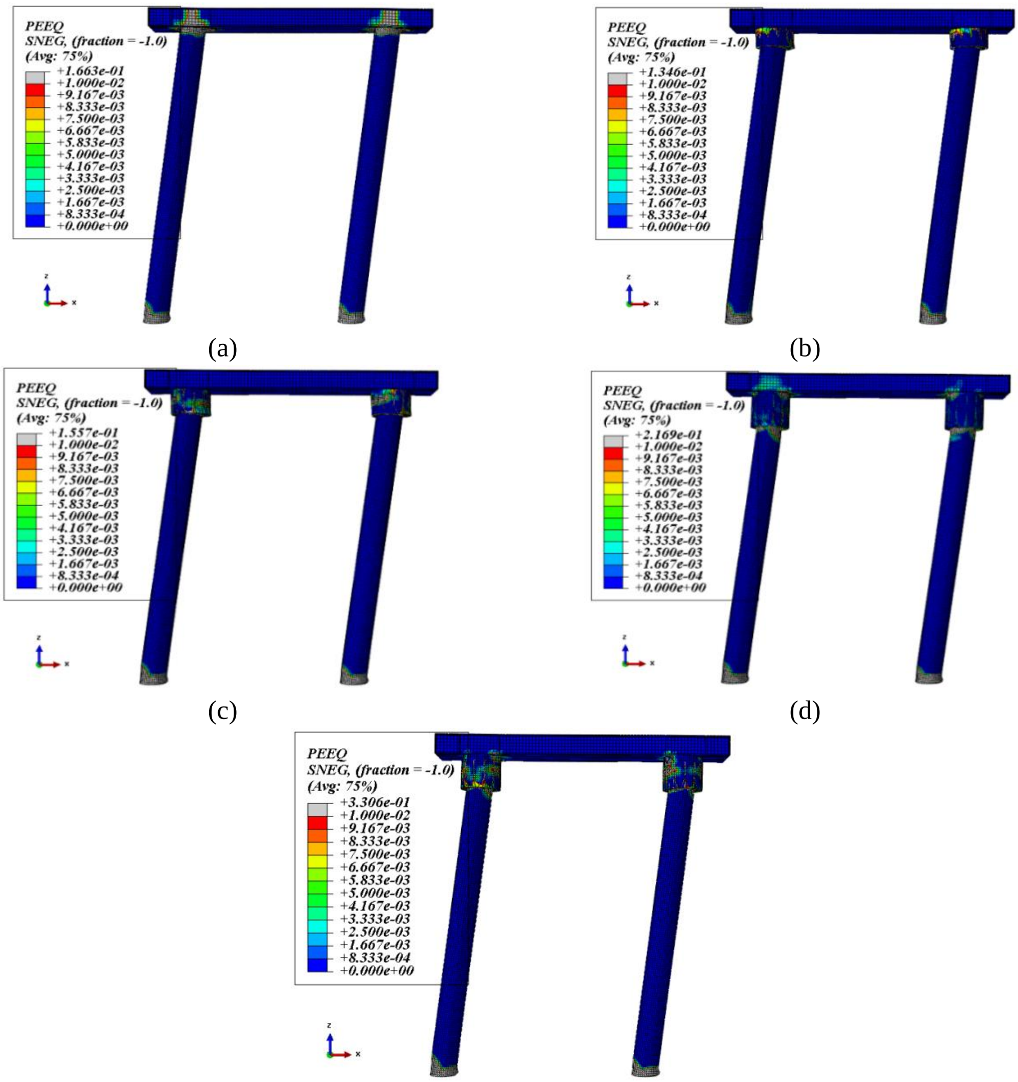


Fig. 11 Equivalent plastic strain (a) WB (b) CB-300 (c) CB-400 (d) CB-500 (e) CB-584

connection for the joint between the pier and superstructure causes the transfer of stress concentration and plasticity from the joint location to the pier. Past experimental studies have shown that if plasticity develops on the interface plate between the pier and superstructure, a sudden failure occurs. Furthermore, it can be seen that the connection with the larger length of the composite region tends to transfer stress concentration and plasticity more effectively. For example, by comparing Fig. 11(b) and 11(e), in a connection with a length of 584 mm (Fig. 11(d)), the area of the plasticity in the joint region is much less.

The energy dissipated in different models has been shown in Fig. 12. As can be seen, the dissipation energy in a direct composite connection (WB) model with composite length of 300 mm, 400 mm, 500 mm, and 584 mm are 3000, 4800, 5100, 5150, and 5300 kN.m, respectively.

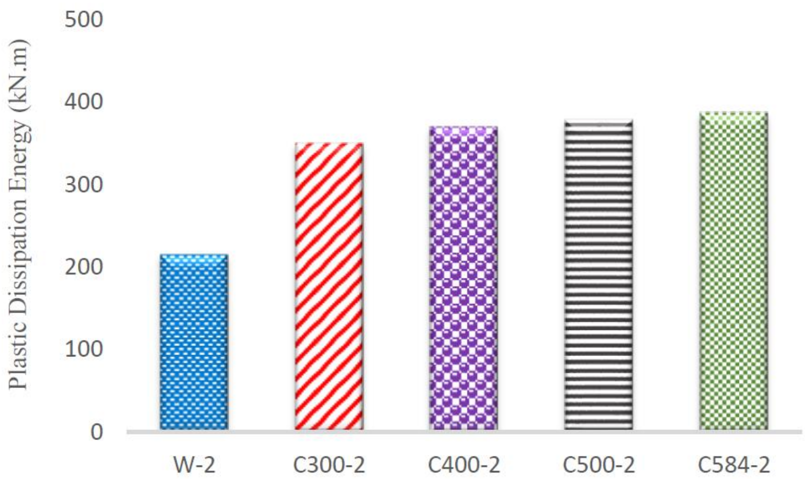


Fig. 12 Dissipated energy in different models

Comparison of the dissipated energy in the models show that the CB-584 connection can dissipate energy 72% more than the WB model. It can therefore be concluded that the composite connection increases the dissipated energy and, consequently, the steel bridge's plasticity in joint region. By comparing the CB-300 and CB-584 models, it can be seen that the length of the composite region from 300 mm to 584 mm increases the energy dissipation by up to 45%.

5. Conclusions

This study deals with the numerical analysis of the composite connection of the pier to the superstructure in steel bridges. Five types of composite connections of the pier to the superstructure were investigated in steel bridges under cyclic loading.

1. In all cases related to the use of composite joints, the structural hysteresis curve has found a higher surface. Although its displacement capacity has remained constant, the force capacity has increased. This increase increases the potential for energy loss in the structure and the structure is more resistant to seismic loads. By comparing the bridges with the direct connection and the composite connection, it can be seen that the composite connection will increase the shear capacity by 20% and the dissipated energy by 45%.
2. It is also observed that when the length of the composite area increases, the shear capacity is increased up to 10%.
3. The results of this study indicate that the use of composite connection transfers stress concentration and plasticity from the connection area to the pier. Moreover, results showed that the connection with the larger length of the composite area tends to transfer stress and plasticity more effectively.

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