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Review on Seismic Behavior of Slab-on-girder Steel Highway Bridges

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Abstract: Damage during the recent earthquake shows the vulnerabilities of steel bridges. The most studies show that transverse seismic loading are transferred via end cross frame to the bearing and shear key which is located on the abutment and bent. As the allowance of thermal movement in the longitudinal direction is the primary operation of the bearing and also they are frequently restrained in the transverse direction, so all this shear force is transmitted to the substructures. New researches are conducted on the slab-on girder steel bridges to indicate the critical component in the lateral load pass. This review shows the findings on the importance of the bearing stiffness, ductile end diaphragm as a fuse element and shear connector in transforming lateral applied load to the end diaphragm.

Key words: Steel bridges, seismic evaluation, ductile end diaphragm, seismic retrofit

INTRODUCTION

Study on the lateral response of the structures under seismic excitation (Adedeji and Ige, 2011; Sasan and Mohammadsadegh, 2011) and/or wind load (Majid *et al*., 2010) is one of the interesting topic that is mentioned by most of the structural engineers. Recent study are conducted to clear the ambiguous point of the lateral performance of the spatial structures such as double layer cylindrical space truss (Jamshidi *et al*., 2011), double layer lattice domes (Jamshidi *et al*., 2012), metro tunnel (Bagherzadeh and Ferdowsi, 2009). Avoiding of seismic evaluation of the special structure in horizontal or vertical direction (Nezamabadi *et al*., 2008) based on the lacking of an appropriate seismic provision and/or situating in the low seismic region (Faisal *et al*., 2011) during their design or construction enhanced the probability of retrofitting in their service time which may need to spending too much money and complex analysis (Amiri *et al*., 2008). Equivalent static loading and dynamic analysis are the most comment methods that used in the seismic analysis of civil engineering structures (Alsulayfani and Saaed, 2009). But it is noticeable that time history analysis is time consuming, spatially when the structural non-linear performance is considered (Majid *et al*., 2010); so some of the researchers presented computer aid (El-Kafrawy and Bagchi, 2007) or try to use some new mathematical method such as wavelet method to mitigate its required time (Nadhim, 2006).

Steel bridge is regarded as anti-seismic structure that using of them is suggested in the high seismic regions because few collapses of the steel bridge are reported during the recent earthquake compare to the concrete bridges. There are a few steel bridges with steel columns; however, the population of them will be increased when steel bridges with concrete column are considered too, nevertheless, the number of them is small compare to the concrete bridges. So there are little data on their seismic performance of them during past earthquakes. Therefore, considering the steel bridge as an anti-seismic system is regarded to the fact that a few of them are exposed to seismic excitation rather than their high-capacity Itani and Bruneau (2004). Some of the designers are believed that the superstructure which is design for the out-of-plan gravity load has adequate resistance against lateral loading; this believed is justified for the concrete superstructure with heavy and stiff features. But slab-on-girder steel bridges are maybe flexible in-plan (Itani and Bruneau, 2004).

Some damages are suffered by steel bridges during the past earthquake such as Kobe (Bruneau and Dicleli, 1996; Shinozuka, 1995; Astaneh-Asl and McMullin, 1994) and show that in some case, they will be more brittle than concrete superstructures (Carden and Itani, 2004). For example, during the Petrolia earthquake, for the southbound Van Duzen River Bridge, the end diaphragm is buckled and near the end of span, the concrete covers are spall at the shear stud connection. Anchorage failure

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of bearing at the abutment and bent cap is reported during Northridge earthquake, buckling of the end diaphragm and failure of the connection in the end cross frame and web stiffeners is observed and minimum damage of the column and pile show that much of the displacement demand was accommodated in the superstructure of each of these bridges. Failure of the concrete substructure, steel piers, bearing and steel girder are typical damages which are observed during Kobe's earthquake. These observations indicted that, most of the steel bridges that constructed in the seismic hazard zone didn't design base on the seismic provision and induced the researcher to conduct the extensive study on the seismic performance of this kind of highway bridges.

Saadeghvaziri and Yazdani-Motlagh (2008) conducted some analytical study on the multi-span-simply-supported bridges and show their variability even under low level of PGA.

Most of the bridge structure's weight is regarded to the massive superstructure, so the main part of the inertia force during a seismic excitation is induced in the heavy slab deck. Transferring this lateral force to the support, involve some of the superstructure components. Detecting critical component in the load path can be used to improve seismic design and optimized cyclic behavior of the steel bridge structures. In this review, the seismic performance of the single span bridges, multi-span continues bridges and multi-span with simply supported bridges which are three common types of slab-on-girder steel bridges, are presented (Fig. 1).

Bearing force and sliding: As the damages of the slab-on-girder bridge are reported during the past earthquake, some researchers started their study to find the reason of these failures. Some study was concluded on the seismic behavior of the single span; multi-span continues (Dicleli and Bruneau, 1995c) and multi-span simply supported (Dicleli and Bruneau, 1995b) steel highway bridges by focusing on the bearing force and sliding of the girders. They state that the stiffness of the fix bearing on the abutment severely affected on the period time of the two-span simply supported bridges and consequently, on their seismic response but by increasing the number of span, the influence of the fix bearing will be negligible (Fig. 2).

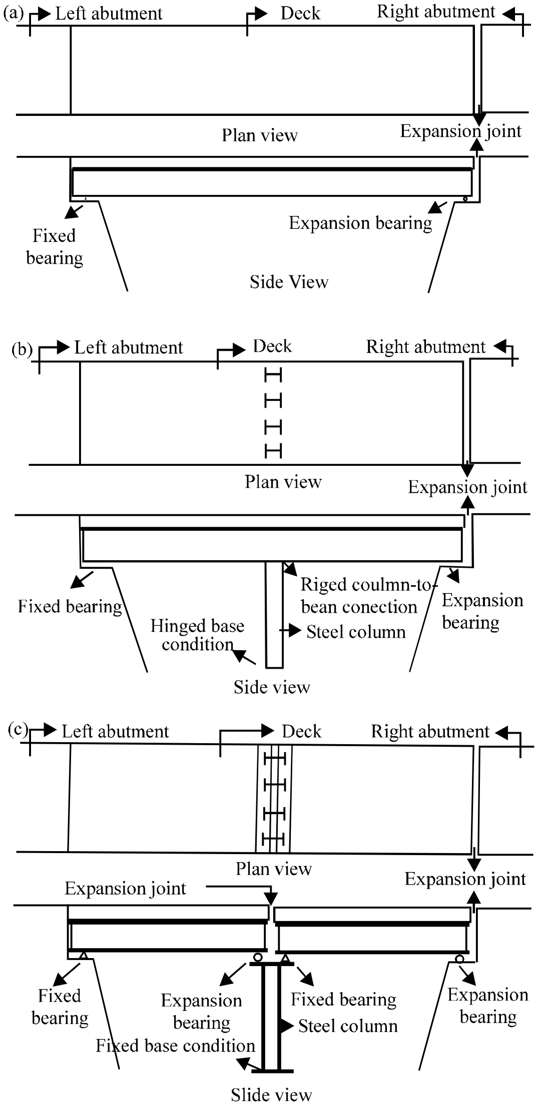

Fig. 1(a-c): (a) Typical single span bridge Dicleli and Bruneau (1995a), (b) Multi span continues steel bridge (Dicleli and Bruneau, 1995c) and (c) Typical two-span simply supported bridge (Dicleli and Bruneau, 1995b)

If the single-span bridge is subjected under transverse excitation, Base on the vectorial summation of the transverse force that induce by transverse reaction and the longitudinal force which is created by the rational resistance of the bearing, Dicleli and Bruneau (1995a) show that the critical bearing is the farthest ones form the bridge centerline (Fig. 3). The ratio of the maximum bearing force (Br) to the m×A_g (which 'm' is the seismic mass of the bridge and Ag is the pick ground acceleration) becomes longer when the stiffness of the bearing increases. By increasing the length of span, this mentioned ratio will be increased but it should be constant for the bearing with zero rational stiffness. The B_r is small in the elastomeric bearing because of their long-period times. They also have shown that the bearing force for the bridge with 2 and 3 lanes is the same if the

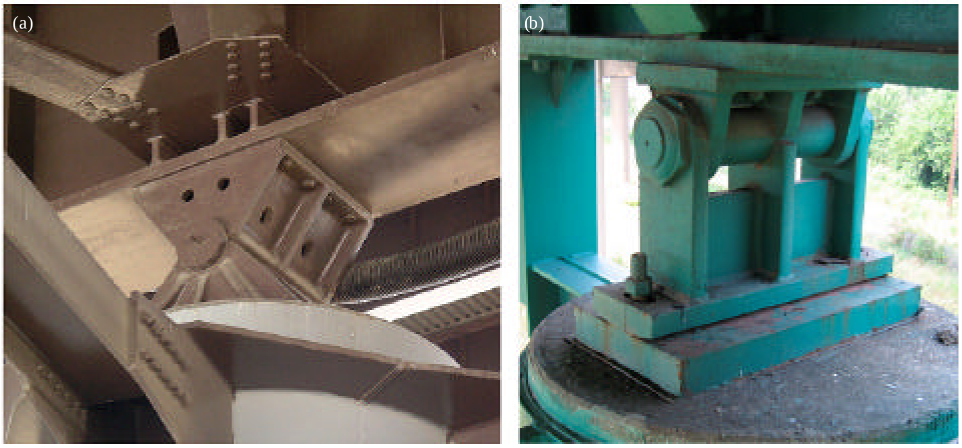

Fig. 2(a-b): (a) Fixed bearing and (b) Rocker bearing (Padgett, 2007)

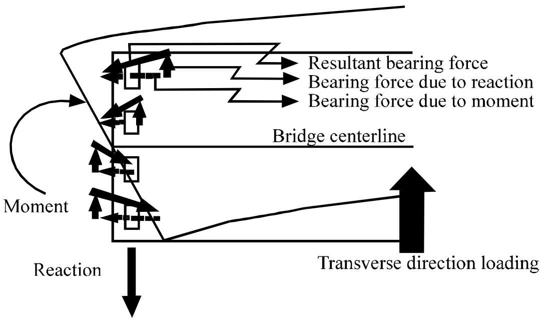

Fig. 3: Bearing force due to the transverse excitation (Dicleli and Bruneau, 1995c)

bearings don't have any longitudinal stiffness but if they have infinite longitudinal stiffness, the bearing force for the 2 lanes bridge is 50% more than 3 lanes bridge. Failure of the bearing is acceptable if they are stable and can slide freely once the anchors are damaged during an earthquake (Bruneau and Dicleli, 1996).

For continues bridges, Dicleli and Bruneau (1995c) show that the variation of the bearing force is similar to the single-span bridge but the exiting difference between bearing force for the 2 and 3 lanes bridge which has bearing with infinite longitudinal stiffness are less than single-span bridges. And for the simply supported continues bridges that have the bearing with infinite rotational stiffness, enhancing the length of the span up to 40 lead to the increasing of the TBFC (maximum transverse-bearing-force coefficient) and TBFC will reduce when the length of span is more than 40 m. In this case (continues bridges), the bearing force for the bridge which consists of 2 lanes is more than the bridges with 3 lanes. It is noticeable that the bearing force is negligible for the bearing with zero rotational stiffness and for this case of the bearing, the number of the lane has not any effect on the bearing force.

In transverse direction, for the same ratio of the friction coefficient to the peak ground acceleration, by increasing the peak ground acceleration and the number of spans, the sliding displacement will be enhanced. On the other hand, decreasing the above ratio resulted to increase of the sliding displacement. Using of the wider bridge can reduce the sliding displacement. The sliding of the narrow longer bridge is noticeable; therefore, in some case, their deck maybe fell down if the seat width is not sufficient; Dicleli and Bruneau (1995a) show that the tendency of a seismic excitation to cause high sliding displacement related to the distribution of an earthquake content which is a function of the velocity time history. Defining a bridge with more spans for the constant total length, increase the sliding displacement. The seismic performance of the continues bridge is severely affected by the magnitude of the friction coefficient; it means that by using a bearing with the high friction coefficients, the seismic capacity of the column will be improved. Regarding to the bearing damage, 2 lanes continue bridge is more vulnerable than 3 lanes ones (Dicleli and Bruneau, 1995c). Dicleli and Bruneau (1996) proposed a methodology to evaluate the seismic performance of slab-on-girder steel bridges.

Slab-on-girder steel bridges without diaphragm: Previously, for calculating the effective stiffness of the bridge's superstructure, the concrete deck and girders are modeled as a beam with an equivalent effective section on the column and/or foundation spring. This theory is acceptable for the concrete bridges and some other

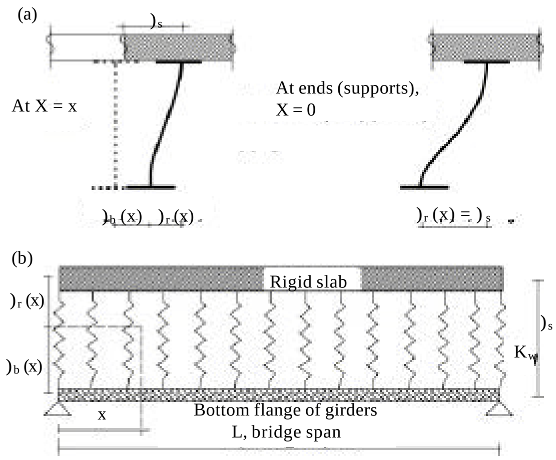

Fig. 4(a-b): (a) Side view of beam deformation and (b) Rigid slab on the elastic foundation (Zahrai and Bruneau, 1998)

bridges but Zahrai and Bruneau (1998) show for the single span simply supported bridge without diaphragm that contrary to the concrete slab which act as a rigid body, steel girders deformed flexible in transverse direction and its deformation is more noticeable near the bearing supports (Fig. 4). The distortion of the steel girder is severe near the bearing supports. So traditional procedure isn't useful for calculating the time period and therefore, appropriate method should be suggested.

Fundamental period: Zahrai and Bruneau (1998) consider the transverse behaviour of the slab and girder as a beam on elastic foundation and proposed Eq. 1 to calculate the lateral deflection (Δ_r is the bottom flange which is simply supported on both ends:

$$\Delta_r(x) = \frac{2R_S\beta}{k_w}\,\frac{\cosh\beta x\cos\beta(L-x) + \cosh\beta(L-x)\cos\beta x}{\sin\beta L + \sinh\beta L} \tag{1}$$

R_s is the reaction of each girder due to the uniform lateral load applied to the deck; L is the span length:

$$\beta = \sqrt[4]{\frac{k_w}{EI_b}}$$

where, k_w is the web stiffness; E is module of the elasticity and I_h is the bottom flange moment of inertia. So for calculating the period of the systems Eq. 2-4 are used:

$$T = 2\pi\sqrt{\frac{m^*}{K^*}} \tag{2}$$

$$m^* = \int_0^L \frac{m}{L}\Delta_S^2 dx = m\Delta_S^2 \tag{3}$$

$$K^* = n_g\left(\int_0^L \frac{12EI_w}{h_w^3}\Delta_r^2(x)dx + \int_0^L EI_b\Delta_b^2(x)dx\right) \tag{4}$$

n_g is the number of girders; I_w and h_w is the web moment of inertia and high, respectively; m is the total mass of the bridge per unit length; Δ_h and Δ_S are shown in Fig. 4.

Effect of the web stiffness: Most of the build-up girders have intermediate web stiffeners which enhance the shear strength of the beam. Zahrai and Bruneau (1998) consider the effect of the stiffed web by equivalent thinner unstiffen web on the seismic response of steel bridges and they show the high effect of the bearing stiffener on the period time of these structures.

Nonlinear response: As the lateral displacements of the heavy concrete slab are large so for this kind of bridge without end diaphragm, the P-Δ effect is more noticeable that may result to the insatiably of the system. Zahrai and Bruneau (1998) show that via end-diaphragms even with small stiffness the superstructure act as an unite body in the elastic range but by failure of the end diaphragms, the seismic behavior change severely and the lateral displacement increased and the P-Δ effect can remove the stability of the bridge. So they continue their study to propose effective ductile end diaphragms.

Slab-on-girder steel bridges with ductile end diaphragm: Using of a ductile end diaphragm over the abutment and piers are suggested by Bruneau *et al.* (2002) as an appropriate strategy to improve the seismic performance of the steel bridges' structures. By conducting full-size testing (Zahrai and Bruneau, 1999a) show that ductile end diaphragms can possess adequate initial elastic stiffness, strength and high capacity of energy dissipation. Base on the experimental result the average ductility of 8 to 10 is derived for the tested end diaphragms (Fig. 5). Analysis show that the effect of the intermediate diaphragm on the seismic performance when there is not any end diaphragm is not considerable (Zahrai and Bruneau, 1998).

Fundamental period: The 'stick' model is proposed to simplify analytical development. This model consists of an end diaphragm, a piece of two steel girder that surrounded the mentioned diaphragm with their bearing stiffness, a stub of the concrete deck and an additional mass/spring system that reflected the effect of longitudinal general mass and stiffness (Fig. 6). The most

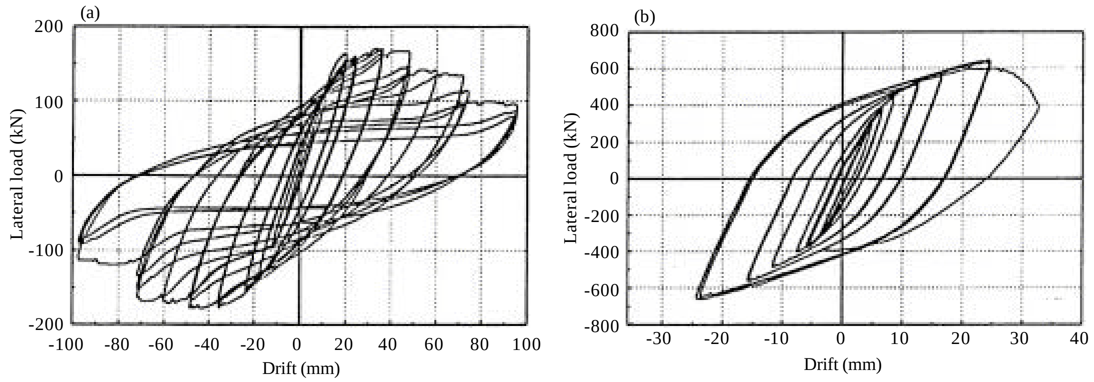

Fig. 5(a-b): (a) Hysteretic diagram for a specimen without end diaphragm and (b) Hysteretic diagram for a specimen with EBF end diaphragm (Zahrai and Bruneau, 1999a)

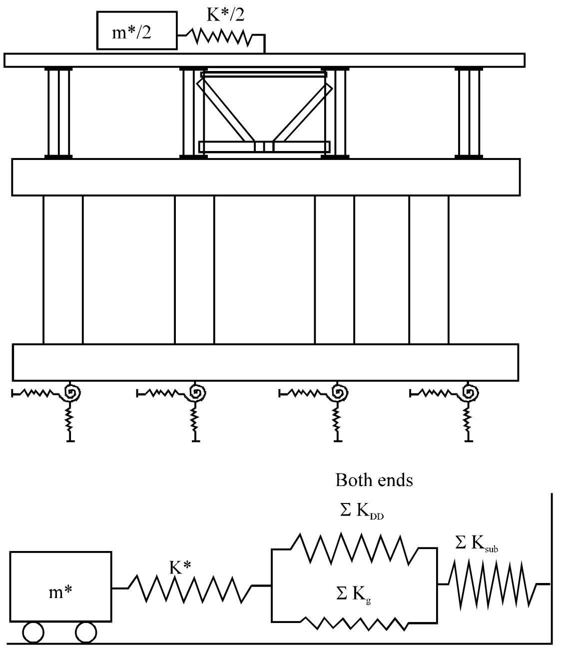

Fig. 6: Spring model of the system, c shows double system (Zahrai and Bruneau, 1999b)

part of the girder stiffness is regarded to the bearing stiffeners, so consider the longer stub-length of a girder doesn't have significant influence on the results (Zahrai and Bruneau, 1999b).

As the general, end-diaphragm and substructure stiffness which are detected by K*, Kends and KSubs are connected together as a series spring model (Fig. 6), so the equal stiffness is derived by Eq. 5:

$$K_e = \frac{1}{\frac{1}{K^*} + \frac{1}{K_{ends}} + \frac{1}{K_{subs}}} \quad (5)$$

For the single span bridge, based on the high stiffness of the abutment, the third term of the denominator can be ignored. As the interaction of the ductile end diaphragm stiffness (K_{DD}) and the girder stiffness (K_g) can be simulated by parallel spring, so Kendsis calculated by Eq. 6:

$$K_{ends} = K_g + K_{DD} \quad (6)$$

Finally, the lateral period time is calculated by Eq. 7:

$$T = 2\pi\sqrt{\frac{m^*}{K_e}} \quad (7)$$

Different kind of ductile end diaphragm: Zahrai and Bruneau (1999b) demonstrate how Eccentrically Braced Frames (EBF), Shear Panel System (SPS) and steel Triangular-plate Added Damping and Stiffness device (TADAS) can be used as seismic resistance systems of single span bridges' substructures (Fig. 7). They also show that it can calibrate to yield before reaching the strength of the abutments.

Carden and Itani (2004), conducted an experimental test to find the efficiency of unbounded brace. The results show that they are stable during transverse lading and limited the structural displacement more than X bracing. The hysteric behavior of them is similar to the EBF, TADAS and SPS end diaphragm but their displacement capacity is more than other diaphragms (Fig. 8).

Using of ductile end diaphragm as a retrofit strategy: Most of the exciting stab-on-girder steel bridges are supported by stiffed vulnerable substructure which expensive method may be required for their retrofitting. (Zahrai and Bruneau, 1999b) show that the lateral transverse load transmitted from the heavy superstructure

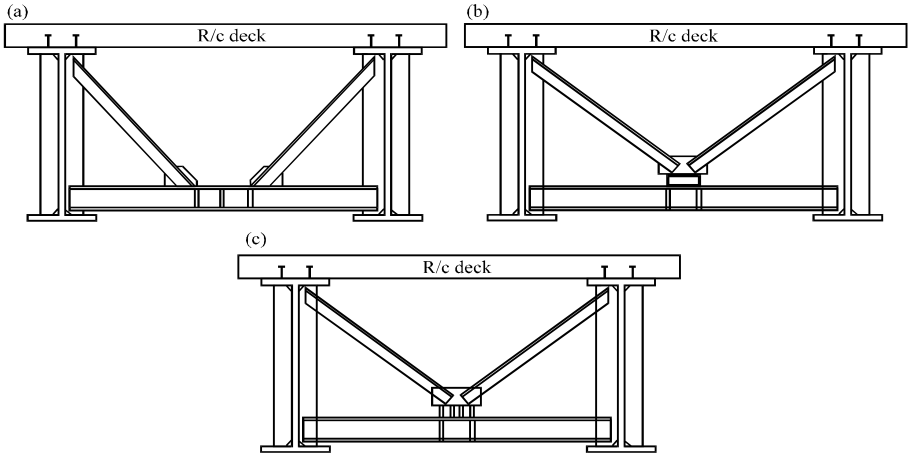

Fig. 7(a-c): (a) Eccentrically braced frames (EBF), (b) Shear panel system (SPS) and (c) Steel triangular-plate added damping and stiffness device (TADAS) (Zahrai and Bruneau, 1999b)

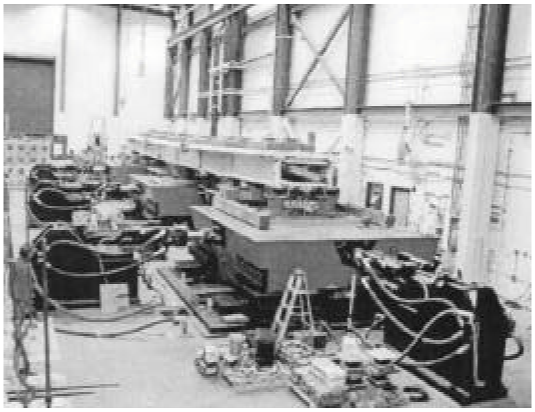

Fig. 8: Use of unbounded brace as an end diaphragm (Carden and Itani, 2004)

to the pier and abutment will be mitigated by using ductile end diaphragm. By calibrating ductile end diaphragm to yield before reaching the ultimate resistance of the substructure, they will act as a structural fuse (Fig. 9).

Ductile end diaphragms which are studied by Zahrai and Bruneau (1999b) can improve the seismic performance of steel bridges in transverse direction and therefore, are useable for retrofitting of the slab-on-girder steel bridge in transverse direction. Celik and Bruneau (2009) proposed a new detail of the ductile end diaphragm by using of Buckling Restrained Braces (BRBs) system which can use as a suitable strategy for retrofitting of the steel bridge under bidirectional seismic loading (Fig. 10).

Composite action: Transferring the lateral load from the concrete slab deck to the bearing support through end diaphragm, highlight the effect of the composite action at the end of spans. As the shear welding stud may fatigue under tension, so for some slab-on-girder bridges, no shear connections are designed in the negative moment. In this reign, the intermediate cross frame which is located between contraflexure point and end diaphragm have a significant action to transmit the transverse loading from top flange of the girder to the bottom flange Itani and Bruneau (2004). Shamshad *et al*. (2007) show that the limited-thick transverse slice model can't capture the real lateral response of the bridge compare to the full model because in the slice model, the second lateral load path consisting of the steel girder, concrete slab and shear connector didn't consider (Fig. 11).

Simplified model for transverse girder displacements at the bridge supports: The efficiency of the end diaphragm is depended to the relative transverse displacement between concrete slabs and bearing support due to the transverse load which is applied at the bridge deck. Considering this deformation show that the transverse stiffness of the girders is depended to the torsional stiffness of the girder (modelled by a translation spring K_t), rotational stiffness of the bearing (modelled by a torsional spring $K_{\theta b}$), flexural stiffness of the bearing stiffeners (modelled by a beam element) and rotational stiffness of the deck or connection between steel girder and concrete slab (modelled by a torsional spring K_{0g}) (Fig. 12). Carden and Buckle (2007) are modelled two different girders at the end of the single-span or continues bridge and a steel girder at the intermediate support; and then calculates the capacity displacement of these girders.

By removing, the portion of the effective cross-section which is required to carry gravity load (Fig. 13), Carden and Buckle (2007) calculated the maximum moment

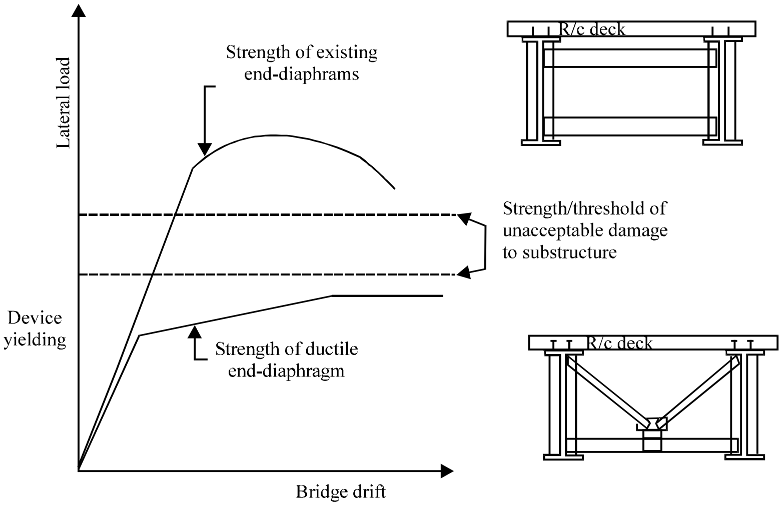

Fig. 9: Bilinear model (Zahrai and Bruneau, 1999b)

Fig. 10: New detail of ductile end diaphragm by using Buckling Restrain Braces (BRBs) (Celik and Bruneau, 2009)

capacity of the bottom which is residual to carry lateral girder deformation and also the allowable girder displacement. For the section between ends of the girder and intermediate cross frame, the maximum stress will be taken place at the bottom flange if the transverse load acts on the system (Carden and Buckle, 2007). Preventing of the girder rotation under concrete slab by using of composite action, cause distress to the shear stud and concrete deck.

To facilitate the rotation of the end of the steel girder, Carden and Buckle (2007) proposed a length in each side of the support without shear stud. By equalling the induced torque (T_f) at the top flange to the ultimate torsional resistance of a row of shear stud (T_{usr}), this mentioned length will be derived:

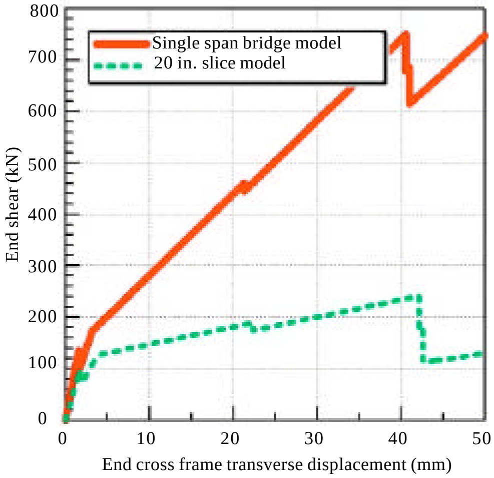

Fig. 11: Push over analysis of slice and full models (Bahrami and Buckle, 2007)

$$T_f = \frac{GJ_{ft}\theta_S}{l_s} \quad (8)$$

$$T_{usr} = P_u \sum r_i \quad (9)$$

For the multi-span steel bridges, Carden and Buckle (2007) show that removing the shear connector in the negative moment reign decrease the transferred base shear to the substructure until 23% compared to the bridge with full composite action. Additional bending stress will be induced in the girder above the bent base on the non-composite action of the slab-on-girder section which may lead to yield or buckle of the flange. For confirming of transition of the transverse load to the end cross frame another element should be considered (Carden and Garcia-Alvarez, 2002). Itani and Bruneau (2004) found that design the top chord of the end diaphragm to provide composite action in the negative zone give a favourite pass in transferring lateral load from the deck to the bearing support. Such an element is proposed by Carden and Itani (2006), who show that by modifying the connection detail of the single angle concentrically brace (Fig. 14), it can be used as a ductile end diaphragm (Carden and Itani, 2006) and also show that using of the buckling restrained braces can improve the hysteresis behaviour of the steel bridges (Carden and Itani, 2006).

Bahrami and Buckle (2007) stated that contribution of the torsional stiffness of the steel girders in the lateral load pass enhanced the transferred shear force to the abutment and piers and it can be reviled by using of decouple ductile end diaphragm. The shear transmitted to the substructure by using such a decoupled end diaphragm (Fig. 15) is around 25% of the shear that transformed with conventional end diaphragm.

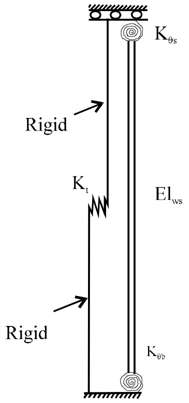

Fig. 12: Simplified model of steel girder at the support (Carden and Buckle, 2007)

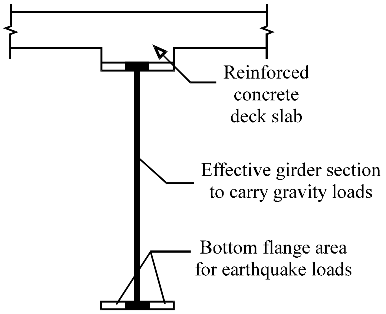

Fig. 13: Dividing cross section for carrying gravity and transverse force (Carden and Buckle, 2007)

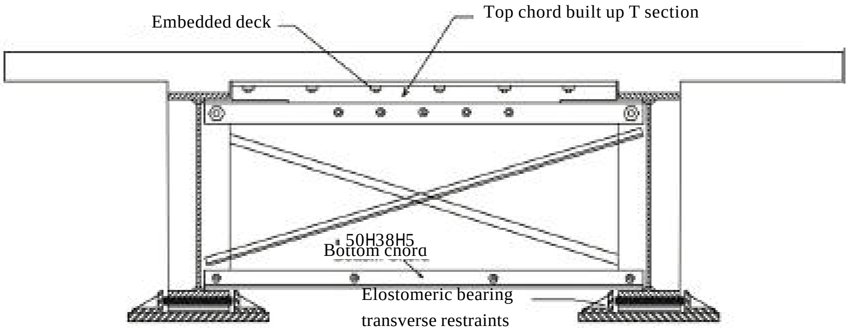

Fig. 14: Modifying the connection detail of the single angle concentrically brace (Carden and Itani, 2006)

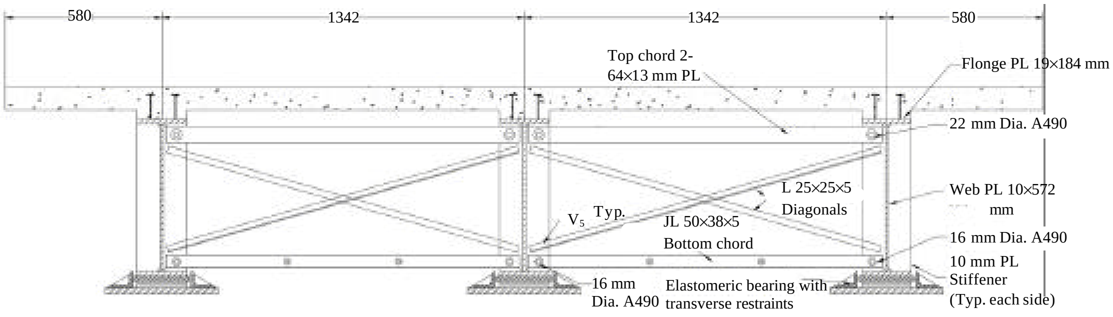

Fig. 15: Decoupled chevron end diaphragm (Bahrami and Buckle, 2007)

CONCLUSION

Recent studies show that absence of the end diaphragm slack the traditional procedure for calculating the period time because of the lacking of the adequate assumptive rigidity. This level of flexibility was enough to enhance the effect of P-Δ that may result to the insatiably of the system. Reported damage of the exciting slab-on-girder steel bridges show that most of them are supported by stiffed vulnerable substructure which, expensive method may be required for their retrofitting. Using of the structural fuse in the lateral load pass such as ductile end diaphragms which are calibrated to yield before reaching the ultimate resistance of the substructure, are proposed as an efficient retrofitting strategy. It also recommended that don't use shear connectors in the negative moment region to exclude of creating distress to the shear stud and concrete deck based on the prevention of the girder rotation. For confirming of transition of the transverse load to the end cross frame another element should be considered to provide composite action in the negative zone.

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