The Third International Bridge Seismic Workshop, 3rd IBSW

Seattle, Washington, USA - October 1st to 4th, 2019

TRIAL DESIGN STUDY ON EARTHQUAKE RESILIENT HIGHWAY BRIDGE WITH TALL PIERS

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Abstract

In this study, the design concept of a new type of bridge is proposed to significantly improve the seismic performance of bridges with tall piers in earthquake-prone areas based on the seismic resilient design. The pier consists of concrete-filled steel tubular (CFST) columns and energy dissipating mild steel plates (EDMSPs). A conventional continuous rigid-frame bridge located in the mountainous area is used as the prototype, based on which a new bridge with the proposed composite tall pier is designed. The seismic performance of the bridge with the newly proposed composite pier and the conventional RC box-section are analyzed and compared under the E2 level earthquake. The results indicate that: (1) Under the fundamental load combination, the bridge with new composite tall piers meet the requirements of structural strength and stability; (2) Under the E2 level earthquake, the bridges with conventional RC hollow section piers will experience medium damage. On the contrast, only the energy dissipating mild steel plates yield in the bridge with the newly proposed composite pier, indicating that the proposed bridge is earthquake-resilient; (3) Furthermore, under the E2 level earthquakes, The relative displacements between the superstructure and the bridge pier in these new bridges are also smaller than the conventional ones.

Keywords: tall-pier bridge; composite pier; energy dissipating mild steel plates; earthquake resilient structure

1. Introduction

In the mountainous areas with very high mountains and very deep valleys, the total length of a highway or railway may be shortened by 200 m to 400 m as the height of pier increases 1 m [1]. Therefore, tall-pier bridges are always the optimal design option in these areas. As a matter of fact, a large number of highway and railway bridges have been built or are under construction in the mountainous areas of the Western China in recent years, and the proportion of the bridges with a pier height of more than 40m is not less than 40% [2]. It can be foreseen that with rapid development in the infrastructure of the Western China in the near future, the number of tall-pier bridges will continue to grow rapidly. However, due to most areas in the Western China are seismic regions with high seismicity and high intensity, those bridges with tall piers have to face great challenge from strong earthquakes.

The seismic design of tall-pier bridges is more complicate than that of conventional bridges. The mass of the pier is often larger than that of the superstructure, which can lead to significant seismic inertial forces. In addition, the mass distribution, high order modes and second order effects play significant roles on structural seismic response. However, less research works had been done on the seismic performance of tall-pier bridges compared with the conventional bridges in the past, and the design codes or specifications for seismic design of tall-pier bridges are still absent. The lack of knowledge on the seismic performance of tall-pier bridges may lead to improper design. For example, the Zipingpu Bridge of the Duwen Expressway suffered severe damage in the 2008 Wenchuan earthquake of China [3], which indicating that there are still many problems existing in the seismic design of the conventional reinforced concrete (RC) tall-pier bridges. In order to improve the seismic performance of conventional RC tall-pier bridges, some new design concepts for tall pier system have been proposed, such as steel box piers [2], double-skin steel-concrete composite box piers [4], RC column-slab composite piers [5], latticed concrete-filled steel tubular (CFST) columns and

CFST composite columns [6]. Although the bridges with these tall piers have better seismic performance and have been used in practical projects, the seismic design concepts and design procedures are not updated.

In recent years, the seismic design concept of bridges has been developed from earthquake resistant or mitigation to the post-earthquake resilient [7]. In addition, seismic resilience is the theme of the 16th World Earthquake Engineering (16WCEE, 2017) [8]. Based on the design concept of the seismic resilience, there are a number of ways to achieve structural resilience after earthquake through adopting rocking structure, self-centering structure, replaceable component and so on. Among them, the concept of replaceable component structure originally put forward by Roeder and Popov [9], who proposed the design concept of "structural fuse" when studying eccentric braced steel frames. Tang et al. [10] firstly proposed the design concept of replaceable steel main tower that consists of steel columns and beams when designing the on the east span of the new San Francisco-Oakland Bay Bridge. McDaniel and Seible [11] found that the steel coupling beam served as a "structural fuse" and yielded under moderate and large earthquakes while the tower column remained elastic. Since then, more and more studies were conducted to develop the replaceable components in bridges. Some typical examples include the bi-steel columns with buckling restrained braces (BRB) and the bi-steel columns with steel energy dissipating coupling beams [12-14]. Xie and Sun [15] applied the double-column piers with buckling restrained braces (BRB) and steel energy dissipating beams in tall-pier bridges. The effectiveness of these replaceable components in controlling the seismic damage was validated through finite element (FE) analyses. Xu et al [16] proposed an energy dissipating tall pier that consisted of sacrificial concrete thin-walled slabs and four-limb concrete columns connected by steel coupling beams. Both pseudo-static tests and numerical simulations were conducted to verify the performance of the tall pier.

In this study, a new type of tall pier, which consists of CFST columns and energy dissipating mild steel plates (EDMSPs), is proposed based on the design concept of seismic resilience. A conventional RC continuous rigid-frame bridge with tall box-section pier located on the highway of mountainous area is taken as the prototype. The bridge is redesigned based by adopting the newly proposed composite tall pier. The static resistance and seismic behaviors of the new composite tall-pier bride are studied by the FE analyses. Furthermore, the seismic performance of the proposed bridge is compared with the conventional RC tall-pier bridge under the E2 level earthquake.

2. Design concept of new composite tall-pier bridge

To date, there is still no commonly recognized definition of tall piers over the world. In this study, the tall pier is defined as a pier that has a height of no less than 35m or a slenderness ratio of more than 60 [17] . The newly proposed composite tall pier consists of a four-limb CFST column and EDMSPs. The EDMSPs serve as both energy dissipating components and sacrificial components. Meanwhile, the I-shape steel beams are installed every 10~15 m to connect the four limbs of the CFST column. The schematic view of the proposed pier is shown in Fig.1.

The structural design concepts of the new composite tall-pier bridge are as follows:

(1) Under serviceability limit states: the four-limb CFST column and the EDMSPs form a box section to provide sufficient flexural and torsional stiffness. Meanwhile, the I-shape steel beams arranged along the height of the pier help to ensure the overall stability of the structure.

(2) Under E1 level earthquake: The structure remains elastic.

(3) Under E2 level earthquake: only the EDMSPs yield. The seismic input energy is dissipated by the hysteretic behavior of the EDMSPs, which in return reduce the stiffness of the pier and mitigate the seismic load. Only slight damage or elastic states are allowed for I-shape steel beams under the E2 level earthquake. And all the other components, including the CFST column, are designed to remain elastic.

In terms of bearing capacity design, the lateral and vertical loads transferred from the superstructure are mainly resisted by the four-limb CFST columns under the basic load combination. Under the seismic load combination, both the lateral and vertical loads are still mainly resisted the four-limb CFST columns, while the EDMSPs and the I-shape steel beams also participate in resisting part of the lateral load.

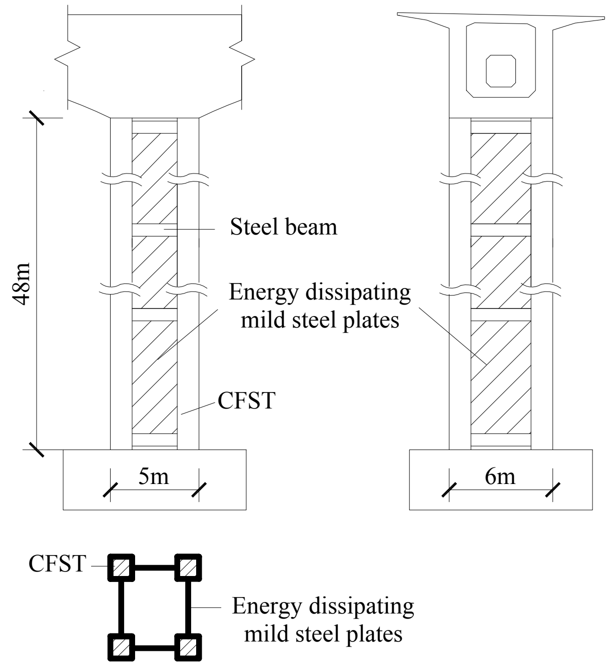

Fig.1 – Concept of innovative pier with composite section

Compared with the conventional RC tall-pier bridge, the advantages of the new composite tall-pier bridge are as follows:

(1) Static performance: the new composite tall pier has the same advantages as the conventional RC/steel box-section tall pier. Meanwhile, due to the vertical axial loads are mainly resisted by the CFST columns, the problem of local bulking in conventional box-section steel pier can be avoided.

(2) Seismic performance: the new composite tall pier has the same advantages as the structure equipped with energy dissipating devices. The EDMSPs help to dissipate the seismic energy and can be replaced quickly. The design concept of seismic resilience for tall-pier bridges can be achieved by properly design.

(3) Construction: the new composite tall pier has the same characteristic of rapid construction as the steel structure.

3. Design of new composite tall-pier bridge

3.1. The prototype bridge

In this study, a tall-pier bridge located at the highway in the mountainous area is used as the prototype as shown in Fig.2. The span arrangement is 57.5 m+105 m+57.5 m. The substructure is a prestressed concrete continuous rigid box-shaped girder, composed of a variable-section single-box section. C50 concrete with a compressive strength of 50 MPa is used in the girder. The height of the girder at the mid-support is 6.0m. It reduces to 2.6m at the mid-span and the end of the side span. The lower edge of the girder is a second-order parabola. The 2#, 3# main piers are RC box-shape section piers constructed with C40 concrete with a compressive strength of 40 MPa. The height of the main pier (i.e., *H*) is 48m. The width of the pier in the in transverse direction (i.e., *a*) is 6m and the longitudinal width (i.e., b) is 5m. The thickness of the box-section (i.e., *t*) is 0.8m. The GPZ(II)3DX and GPZ(II)3SX supports are installed on the1# and 4# piers.

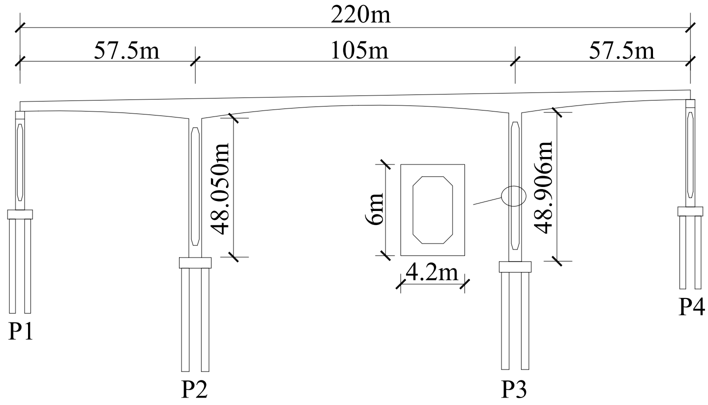

Fig.2 –Layout of the prototype bridge

3.2. Redesign of the prototype bridge

In order to improve the earthquake resilience of the prototype bridge, the proposed new composite tall pier is adopted to replace the original RC box-section pier. Note that the other parts of the bridge remain unchanged. In order to better compare with the original bridge, the following principles are followed when designing the new composite section tall pier:

(1) The axial load bearing capacity of the new composite tall pier is equivalent to the prototype pier;

(2) The height and flexural stiffness in the longitudinal direction of the new composite tall pier are equivalent to those of the original one.

Based on the above design principle, the structural details of the new composite tall pier were determined as follows: (1) Q345 steel and C50 concrete are used in the four-limb CFST column. The sectional dimension is 1.2m×1.2m with a thickness of 25mm. The sectional steel ratio is 8.16%. The EDMSP between the concrete-filled steel tubular columns is made of LYP100 low-yield point steel plate with a thickness of is 25mm. The mechanical properties of the LYP100 are shown in Table 1, which meets the requirements of “Low yield strength steel plate for construction” (GB/T 28905-2012). In addition, the Q345 I-shaped steel beams with a sectional dimension of 400×146×14.5/16.5mm are installed every 12m along the height of the pier.

Table 1 – Basic mechanical properties of LYP100 steel

Yield strength	**Tensile strength**	**Elongation ratio**	**Impact property**
81MPa	239MPa	55%	193J

It is calculated that the axial compression ratios of the conventional RC tall pier and the new composite tall pier are 0.192 and 0.199, respectively. Hence, the axial compression ratio is considered to be the same for the two types of tall pier. Moreover, the longitudinal flexural stiffness of the conventional RC box section tall pier and the new composite tall pier is computed as 1.07×109kN·m^2 and 1.02×109kN·m^2, respectively. Therefore, the new composite tall-pier bridge has similar sectional properties as those of the conventional one.

3.3. Static analysis of the new composite tall-pier bridge

The static analysis of the new composite tall-pier bridge model is implemented in Midas Civil2019. The P-Δ effect is considered in the analysis of the construction process.

According to the "Technical specification for structures with concrete-filled rectangular steel tube members" (CECS 159:2004), the bending moments of the principal plane of a rectangular concrete filled steel tubular column should meet the requirements of Eq. (1) and Eq. (2) simultaneously:

$$\frac{N}{N_{\mathrm{un}}}+(1-\alpha_{\mathrm{c}})\frac{M}{M_{\mathrm{un}}}\leq\frac{1}{\gamma} \tag{1}$$

$$\frac{M}{M_{\mathrm{un}}}\leq\frac{1}{\gamma} \tag{2}$$

where N is the design value of the axial compressive force; M is the design value of the bending moment; α_c is the working load factor of the concrete; N_{un} is the designed value of the sectional compressive bearing capacity; M_{un} is the design value of the sectional flexural capacity; γ is the structural importance coefficient, which is taken as 1.1.

At the same time, Eq. (3) should also be met to ensure the out-of-plane stability:

$$\frac{N}{\phi N_{\mathrm{un}}}+\frac{\beta M}{1.4M_{\mathrm{un}}}\leq\frac{1}{\gamma} \tag{3}$$

where φ is the compression stability coefficient; β is the equivalent bending moment coefficient.

Table 2 lists the design combination of the internal forces of the new composite tall pier under the basic load combination. The results indicate that the four-limb CFST column meets the requirements of the load bearing capacity and stability.

According to the calculation results, the maximum Mises stress of the EDMSP under the basic load combination is 76.2 MPa, which is less than the yield design value of 81 MPa. Hence, the EDMSP remain elastic under such condition.

4. Seismic performance analysis

4.1.FE models of the bridges

The FE models of the prototype bridge and the new bridge with the proposed composite tall piers are established in ABAQUS. For the conventional RC tall-pier bridge, the B31 elements (i.e., 2-node three-dimensional first-order Timoshenko beam element) are used to model the girder. The girder is assumed to remain elastic. Furthermore, the tall piers are also modeled by the B31 element. The reinforcement is defined on the B31 element by the *rebar keyword. The Concrete02 model and the USteel01 model (kinematic hardening elastoplastic uniaxial constitutive model) in the PQ-Fiber subroutine developed by the Department of Civil Engineering of Tsinghua University are adopted for the constitutive models of concrete and steel, respectively. The basin type support is simulated by Cartesian link element. The stiffness is infinite along the fixed direction. In the active direction, the bidirectional ideal elastoplastic model is adopted for the link element.

For the new composite tall-pier bridge, the superstructure and the basin type support adopt the same modeling strategy as the prototype bridge. The four limbs of the CFST column and the I-shape steel beams are also modeled by the B31 element. The steel tube is defined by the *rebar keyword. The USteel01 material in the PQ-Fiber subroutine is adopted for the steel tube. Meanwhile, the confinement effect of the concrete is considered by the constitutive model proposed by Han[18]. The EDMSPs are modeled by the S4R shell elements. Nine Simpson integral points are defined along the thickness of the shell. The bi-linear plastic material with Von Mises yield criterion in ABAQUS is used for the I-shape steel beam and EDMSP. The connections between the EDMSPs and CFST limbs/steel beam are modeled using the "tie" command.

Furthermore, the influence of the soil-structure interaction is considered by the equivalent boundary spring element at the bottom of the pier. In addition, the effects of structural geometric nonlinearities are considered in the analyses.

Table 2 – Design forces and checking results of CFST Columns

Control section	Internal force type	Design combination of the interal forces		Results	
		Axial force/ kN	Bending moment/ kN·m	Equation (1)	Equation (3)
Left limb (top)	Maximum axial force	15461	-3468	0.342	0.689
	Minimum axial force	4368	-1753	0.120	0.226
	Maximum bending moment	4626	-1324	0.111	0.218
	Minimum bending moment	15202	-3897	0.351	0.697
Left limb (bottom)	Maximum axial force	13064	924	0.228	0.501
	Minimum axial force	1967	2373	0.102	0.166
	Maximum bending moment	6419	3392	0.201	0.365
	Minimum bending moment	8612	-95	0.135	0.309
Right limb (top)	Maximum axial force	13265	-2820	0.289	0.585
	Minimum axial force	3181	2731	0.131	0.224
	Maximum bending moment	5521	2853	0.171	0.312
	Minimum bending moment	10163	-3047	0.248	0.484
Right limb (bottom)	Maximum axial force	20660	-635	0.336	0.759
	Minimum axial force	8613	2788	0.216	0.419
	Maximum bending moment	12887	3588	0.306	0.603
	Minimum bending moment	15376	-1317	0.276	0.599

Based on the above FE models, the modal analyses are firstly conducted to compare the dynamic properties of the conventional RC tall-pier bridge and the new composite tall-pier bridge. The results are summarized in Table 3, indicating that the two bridges have similar dynamic properties.

Table 3 – Comparison of the vibration modes

Modal number	Period (s)		Vibration mode
	Conventional RC tall-pier bridge	New composite tall-pier bridge	
1	2.191	2.072	1st-order transverse symmetrical bending
2	1.676	1.635	1st-order vertical bending
3	1.262	1.243	1st-order transverse anti-symmetric bending

4.2. Seismic response analysis

4.2.1. Ground motion input

According to the site condition of the prototype bridge, three sets of ground motion are selected based on the I-class site, of which 2 sets are natural ground motion records and the other one is an artificial for ground motion sets. The magnitudes of the selected ground motions are adjusted according to the seismic design intensity of the bridge (i.e., VIII degree). Each ground motion set contains three components and all three components are input simultaneously. The bridges are analyzed under both E1 and E2 level earthquake. The maximum seismic responses under 3 sets of ground motions are recorded.

4.2.2. Seismic responses under E1 level earthquake

For the RC box-section tall-pier bridge, the maximum curvature in longitudinal direction at the top of the main pier is 1.275e-4. The maximum curvature in transverse direction of the bridge is 1.392e-6. Both of the curvature values are less than the yield curvatures. Note that according to the bending moment-curvature analysis results, the yield curvatures of the main pier in longitudinal and transverse directions are 5.606e-4 and 3.910e-4, respectively. At the bottom of the bridge, the maximum curvature in the longitudinal direction is 1.144e-4, while it is 3.801e-5 in the traverse direction. Both values are less than the yield curvatures (5.821e-4 and 4.4047e-4 in the longitudinal and transverse directions, respectively). Therefore, the RC tall-pier bridge remains elastic under E1 level earthquake.

For the new composite tall piers, under E1 level earthquake, the maximum curvature at the top and bottom of the main pier are 5.296e-4 and 2.390e-4, respectively. Both values are less than the yield curvature (2.703e-3 and 2.775e-3, respectively). Meanwhile, the maximum stress of steel beam is 75MPa, which is less than its yield stress (345MPa). The maximum stress of EDMSPs is also less than its yield stress (81MPa). Therefore, the new composite tall-pier bridge is still in elastic state. Table 4 compares the maximum displacement responses of bridge under E1 level earthquake. The results indicate that the lateral displacements of the new composite tall-pier bridge are smaller than the conventional RC tall-pier bridge.

Table4 – Comparison of maximum lateral displacements under E1 level earthquake

Position	**Direction**	**Maximum displacement/cm**		**Ratio**
		Conventional RC tall-pier bridge	**New composite tall -pier bridge**	
Top of piers	Longitudinal	6.31	4.71	-25%
Top of piers	Transverse	5.58	2.73	-51%
Relative displacement between superstructure and piers		8.73	6.99	-20%

4.2.3. Seismic response under E2 level earthquake

For the conventional RC tall-pier bridges, the modified Park-Ang damage index is used to define the damage state of the main pier [19]. Table 5 lists the damage index and corresponding damage levels of the control section of the RC box-section main pier under the E2 level earthquake. It can be seen from Table 5 that moderate damage occurs in the 2# and 3# main piers under the E2 level earthquake.

For the new composite tall piers, under the E2 level earthquake, the maximum curvatures at the top and bottom of the CFST column in the main pier are 1.243e-3 and 1.096e-3, respectively, which are smaller than the yield curvature. Therefore, the four limbs of the CFST columns remain elastic. The maximum Mises stress of the steel beam is 220 MPa, which is less than the yield stress (345 MPa). Thus, the steel beams also remain elastic. Fig.3 shows the typical Mises stress distribution of the EDMSPs under E2 level earthquake. The EDMSPs have yielded to a large extent and help to dissipate the seismic energy.

Table 5 – Damage indices and corresponding damage states of RC main piers

Main pier	Control section	Longitudinal		Transverse	
		Damage index	Damage level	Damage index	Damage level
2#	Bottom	0.28	Moderate	0.36	Moderate
	Top	0.13	Slight	0.00	No
3#	Bottom	0.29	Moderate	0.39	Moderate
	Top	0.14	Slight	0.00	No

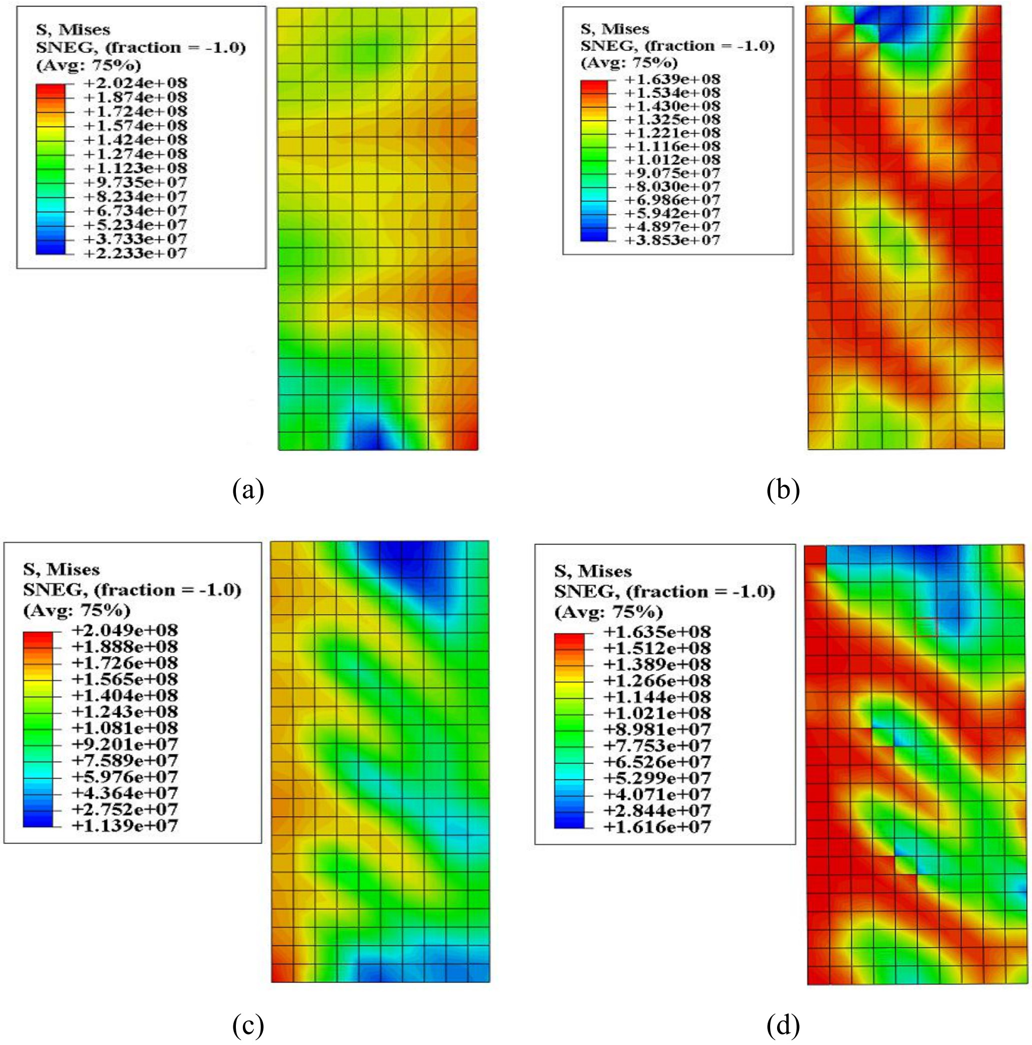

Fig.3 – Stress distribution of the EDMSPs: (a) bottom plate (longitudinal); (b) top plate (longitudinal); (c) bottom plate (transverse); (d) top plate (transverse)

Both the maximum displacement responses of the bridges under E2 level earthquake are summarized in Table 6. The maximum displacement of the new composite tall-pier bridge is significantly smaller than that of the conventional one under E2 level earthquake. Furthermore, after adopting the new composite tall pier, the maximum displacements of the main pier in the longitudinal and transverse directions are reduced by 35% and 58%, respectively. And the maximum relative displacement between the girder and the side pier is reduced by 25%.

Table 6 – Comparison of maximum lateral displacements under E2 level earthquake

Position	Direction	Maximum displacement/cm		Ration
		Conventional RC tall-pier bridge	New composite tall -pier bridge	
Top of piers	Longitudinal	33.96	22.06	35%
Top of piers	Transverse	45.21	18.98	58%
Relative displacement between superstructure and piers		39.20	29.58	25%

5. Conclusions

Based on the design principle of seismic resilient structure, the structural design concept of a new type of composite tall pier, which consists of four-limb CFST column and EDMSPs, is proposed in this study. A typical tall-pier bridge in mountainous area is used as the prototype and redesigned with the new composite bridge. Both static and seismic performances of the conventional RC tall-pier bridge and the new composite tall-pier bridge are compared. The main conclusions are as follow:

(1) Under basic load combination, the new composite tall-pier bridge can provide a satisfying load bearing capacity and stability.

(2) Under E1 level earthquake, the new composite tall-pier bridge remains elastic and has smaller lateral displacement response than the conventional RC box-section tall-pier bridge.

(3) Under E2 level earthquake, the main pier of the conventional RC box-section tall-pier bridge experiences moderate damage. While in the new composite tall-pier bridge, only the replaceable EDMSPs experience a large extent of plastic deformations, indicating the characteristic of seismic resilient.

(4) Under E2 level earthquake, the new composite tall-pier bridge has a small displacement response than the conventional RC box-section tall-pier bridge due to the additional damping provided by the EDMSPs.

6. Acknowledgements

The authors gratefully acknowledge the National Natural Science Foundation of China (Grant Nos. 51878180), and the Transportation Science and Technology Development Project of Fujian Province (Grant Nos. 201803).

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