Steel and Composite Structures, *Vol. 20, No. 3 (2016) 719-729*
DOI: http://dx.doi.org/10.12989/scs.2016.20.3.719

Analysis of seismic behavior of composite frame structures

Huiling Zhao*

Department of Civil Engineering, Shanghai University,
No. 149, Yanchang Rd, Shanghai University, Shanghai, 200072, China

(*Received August 26, 2015, Revised November 18, 2015, Accepted November 27, 2015*)

Abstract. There are great needs of simple but reliable mechanical nonlinear behavior analysis and performance evaluation method for frames constructed by steel and concrete composite beams or columns when the structures subjected extreme loads, such as earthquake loads. This paper describes an approach of simplified macro-modelling for composite frames consisting of steel-concrete composite beams and CFST columns, and presents the performance evaluation procedure based on the pushover nonlinear analysis results. A four-story two-bay composite frame underground is selected as a study case. The establishment of the macro-model of the composite frame is guided by the characterization of nonlinear behaviors of composite structural members. Pushover analysis is conducted to obtain the lateral force versus top displacement curve of the overall structure. The identification method of damage degree of composite frames has been proposed. The damage evolution and development of this composite frame in case study has been analyzed. The failure mode of this composite frame is estimated as that the bottom CFST columns damage substantially resulting in the failure of the bottom story. Finally, the seismic performance of the composite frame with high strength steel is analyzed and compared with the frame with ordinary strength steel, and the result shows that the employment of high strength steel in the steel tube of CFST columns and steel beam of composite beams benefits the lateral resistance and elasticity resuming performance of composite frames.

Keywords: CFST columns; composite frames; damage identification; macro-model; nonlinear analysis

1. Introduction

Steel-concrete composite frame structures can significantly enhance both structural and economic efficiency when compared to the more traditional steel or concrete solutions. Steel-concrete composite beams combine steel beams and reinforced concrete slabs by shear studs to gain large strength and lateral stiffness. Concrete filled in steel tube columns provide higher bearing capacity since the concrete prevents local buckling of steel tubes and steel tubes provides confinements to the concrete and prohibits concrete spalling. Experimental studies on seismic behavior of composite structures have been reported by Zhou *et al*. (2015), Qin *et al*. (2014) and Men *et al*. (2015). It was shown that with remarkable ductility and energy dissipation, steel-concrete composite frames have favorable seismic performance.

Pushover analysis has been regarded as one of the efficient and significant methods to study the structural seismic behaviors (Kalkan and Kunnath 2007, Reyes and Chopra 2011). Pushover

*Corresponding author, Ph.D., E-mail: : hlzhao@shu.edu.cn

http://www.techno-press.org/?journal=scs&subpage=6 ISSN: 1229-9367 (Print), 1598-6233 (Online)

analysis of steel-concrete composite frames involves nonlinear response of composite structure. The interactions of all different components are essential and critical actions for the composite members. However, they bring complexities and challenges for nonlinear analysis of composite structural system. Most of the nonlinear analysis models for composite structures can be broadly categorized into micro-models applied with continuum FEM (Baskar *et al*. 2002, El-Lobody and Lam 2003, Nie *et al*. 2008), and macro-models, for example, line (frame) elements and spring connection (El-Tawil and Deierlein 2001, Valipour and Bradford 2012, Santoro and Kunnath 2013). As for the overall composite frame structures, simple yet reliable macro-models can provide a useful analytical tool for simulating frame nonlinear behaviors to enable high efficient pushover analysis.

As the evaluation of the seismic performance of the overall composite frame through pushover analysis is concerned, previous research (Leon and Hu 2011) employed base shear strength and story drift, which provides guidance for routine design for a set of archetypical frames. However, the evaluation in terms of damage, deformation and strength is comprehensive and helpful to recognize clearly source of over- and under-strength in the composite frame, especially for infrequently encountered frame.

This study is concerned with the seismic performance evaluation of composite frames consisting of steel concrete composite beams and CFST column frames, based on the damage, deformation and strength of composite structures. It is based on pushover analysis by means of the developed composite frame macro-model accounting for the effects of composite actions of concrete and steel components and the nonlinear behaviors of composite connections.

2. Modelling of the composite frames for pushover analysis

2.1 Developed macro-model of composite frames

The simplified macro-model employed in pushover nonlinear analysis is capable of simulating the material nonlinear responses, interactions between components of composite structural members, the load transfer mechanism between composite structural members.

The composite beam model proposed can incorporate an interface shear connection deforming along the beam length, which is modelled by means of nonlinear springs and constraints. As shown in Fig. 1(a), the simplified macro model is assembled by several sets of nonlinear beam-column elements, layered shell elements, rigid beam elements and spring elements. Details of the procedure to arrange the springs as well as compute the unloading and reloading parameters to characterize cyclic behaviour of steel and concrete fibres are described in research of Zhao *et al*. (2010). Nonlinear fibre beam-column elements are used to model CFST column as shown in Fig. 1(b). An assembly of springs and rigid beams are used to model the panel zone as shown in Fig. 1(c).

A simplified model for composite beam-to-CFST column connections is presented to enable predictions of the inelastic response of the panel zones as well as the transfer of shear, moment, and axial forces between column and beam members. The connection model is comprised of four rigid bars whose ends are pined together at the two diagonal corners to permit the desired shear deformation to occur, while at the other two diagonal corners the bar ends are joint by rotational shear springs. As the determination of spring properties is concerned, it is guided by the mechanical characteristics of the composite connections.

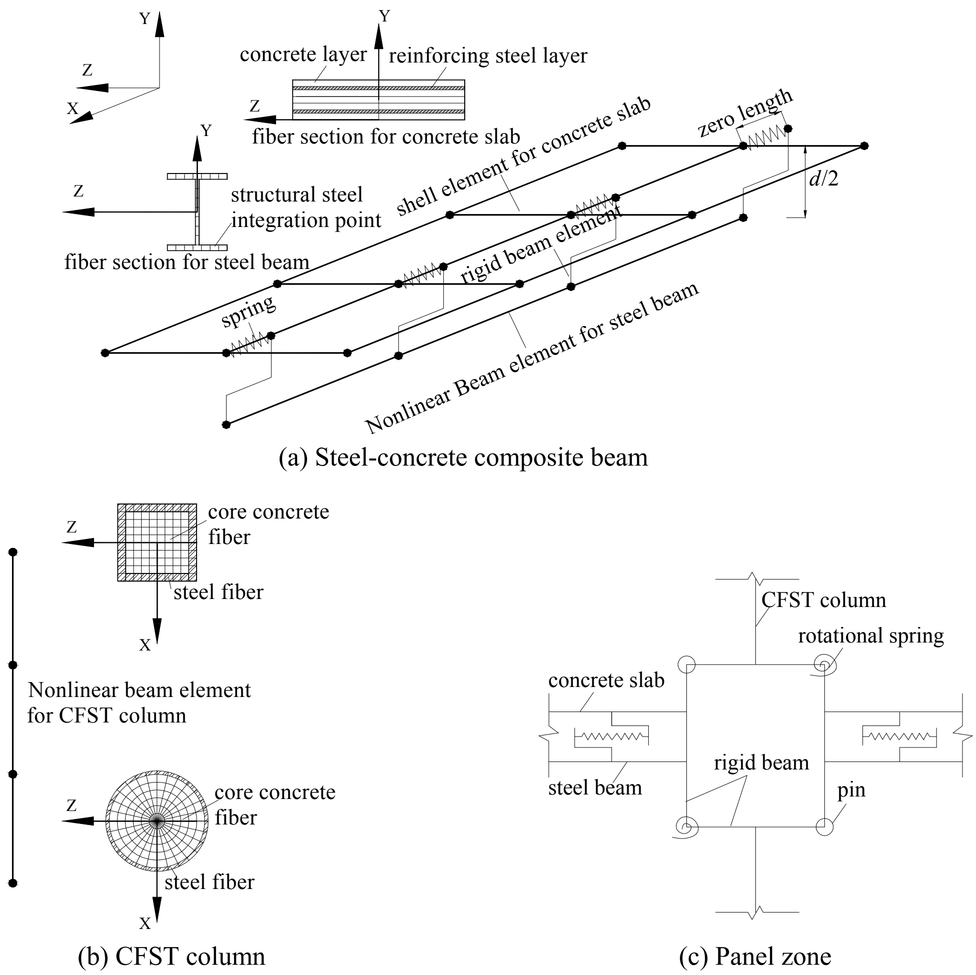


Fig. 1 Description of simplified macro model

2.2 Macro-model of a prototype composite frame

A four-story two-bay composite frame structure in 2D is analyzed as an example. The elevation of this composite frame is shown in Fig. 2. The width and height of the structure is 30 m and 29 m respectively. The span of the composite beams is 15 m. This structure is an underground structure, and the overburden soil depth is 2.0 m.

In order to carry heavy loads and offer large space, this underground frame prefers to employ composite beam and column members rather than reinforce concrete beams and columns. High strength concrete is used for CFST columns to improve the capacity of columns.

This composite frame consists of steel-concrete composite beams and CFST columns. As for the 2nd, 3rd and 4th story underground, the composite beams are composed by a reinforced concrete slab with the thickness of 250 mm and a steel beam, with 800 mm × 300 mm × 22 mm × 14 mm cross section, connected by 16 mm diameter shear studs. As for the 1st story underground, the composite beams are composed by a 300 mm-thick reinforced concrete slab and a steel beam

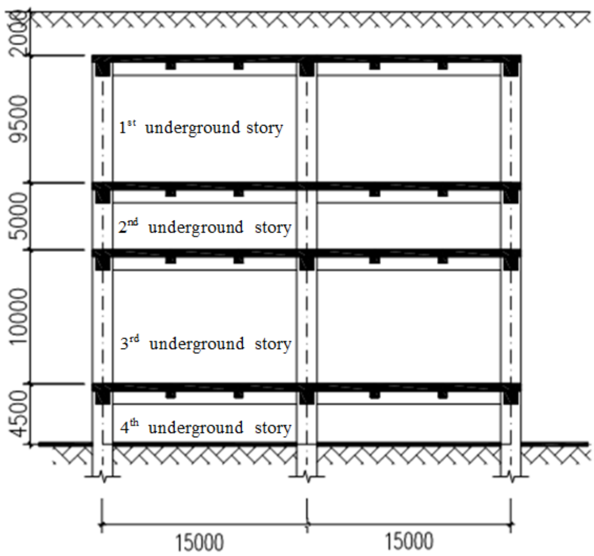


Fig. 2 The elevation of composite frame structure in case study (Units: mm)

with 1100 mm × 400 mm × 25 mm × 16 mm cross section. As for the 3rd to 4th story underground, the diameters and thickness of the CFST columns are 900 mm and 14 mm respectively, and as for the 1st and 2nd story underground, the diameters and thickness of the CFST columns are 800 mm and 12 mm respectively. The yield strength of steel material used for composite beams and CFST columns is 345 MPa. As for all the four stories, the compressive strength of concrete material used for concrete slab of the composite beams is 30 MPa. The compressive strength of concrete material employed for concrete filled inside steel tubes of the CFST columns is 60 MPa.

The macro-model of this composite frame is implemented by the developed macro-modelling scheme using the commercial software LS-DYNA. Composite beam and column members are represented by Hughes-Liu beam-column elements with cross section integration. This element formulation represents inelastic behaviors at one-point along the axis of the beam-column element and at multiple points across the cross section. Inelasticity of materials can be realized by applying suitable material models stated above for the constituent materials into the corresponding fibers across composite cross sections. A framework incorporating MDOF (multiple degrees of freedom) nonlinear discrete springs and rigid body constrains can account for force transfer mechanism of beam-to-column composite joints and complex interactions at interface between steel beam and concrete slab. The macro-model material properties computed for the composite frames are listed in Table 1. The detailed calculating procedure of these values for steel-concrete composite beams, CFST columns, and the beam-to-column composite joints can be found in literature (Zhao *et al*. 2010).

2.3 Pushover analysis

Pushover analysis of this composite frame is conducted to obtain the base shear versus top displacement curve of the overall structure, to search local deformation of the composite beams, columns, and joints, and to acquire sequence of appearance and location of the plastic hinges. According to these data, the seismic performance of this composite frame is evaluated

Table 1 Material properties for the macro-model of the composite frames

<table>
<tr><td rowspan="2">Concrete fibre in slabs</td><td colspan="2">σ_c (MPa)</td><td>ε_c</td><td>σ_{cu} (MPa)</td><td>ε_{cu}</td><td>σ_t (MPa)</td></tr>
<tr><td colspan="2">30.0</td><td>0.0022</td><td>3.0</td><td>0.0050</td><td>2.8</td></tr>
<tr><td rowspan="2">Steel fibre in steel beams</td><td colspan="2">E_s (GPa)</td><td>σ_y (MPa)</td><td>ε_{sh}</td><td>σ_{ult} (MPa)</td><td>ε_{ult}</td></tr>
<tr><td colspan="2">200</td><td>345.0</td><td>0.05</td><td>420.0</td><td>0.20</td></tr>
<tr><td rowspan="2">Spring for shear connection</td><td colspan="2">F_y (kN)</td><td>S_y (mm)</td><td>F_u (kN)</td><td>S_u (mm)</td><td>τ_{fr} (kN)</td></tr>
<tr><td colspan="2">127.5</td><td>1.0</td><td>136.5</td><td>4.8</td><td>12.8</td></tr>
<tr><td rowspan="3">Concrete fiber in CFST column</td><td colspan="2" rowspan="2">3rd and 4th underground story</td><td>f'_{cc} (MPa)</td><td>ε_{cc}</td><td>$\alpha f'_{cc}$ (MPa)</td><td>ε_{ccu}</td></tr>
<tr><td>55.4</td><td>0.0046</td><td>46.3</td><td>0.037</td></tr>
<tr><td colspan="2">1st and 2nd underground story</td><td>55.7</td><td>0.0045</td><td>46.4</td><td>0.037</td></tr>
<tr><td rowspan="2">Steel fibre in steel tubes</td><td colspan="2" rowspan="2"></td><td>σ_{sy} (MPa)</td><td>ε_{sy}</td><td>σ_{st} (MPa)</td><td>ε_{st}</td></tr>
<tr><td>373</td><td>0.0019</td><td>313</td><td>0.0015</td></tr>
<tr><td rowspan="9">Spring for beam-to-column joint</td><td colspan="2"></td><td>M_{py} (kNm)</td><td>γ_{py}</td><td>M_{pu} (kNm)</td><td>γ_{pu}</td></tr>
<tr><td rowspan="2">4th underground</td><td>Positive</td><td>3288.9</td><td>0.0025</td><td>5593.4</td><td>0.0152</td></tr>
<tr><td>Negative</td><td>2917.4</td><td>0.0025</td><td>5091.4</td><td>0.0141</td></tr>
<tr><td rowspan="2">3rd underground</td><td>Positive</td><td>3288.9</td><td>0.0025</td><td>5593.4</td><td>0.0152</td></tr>
<tr><td>Negative</td><td>2917.4</td><td>0.0025</td><td>5091.4</td><td>0.0141</td></tr>
<tr><td rowspan="2">2nd underground</td><td>Positive</td><td>2399.1</td><td>0.0025</td><td>4046.3</td><td>0.0165</td></tr>
<tr><td>Negative</td><td>2129.4</td><td>0.0025</td><td>3690.7</td><td>0.0142</td></tr>
<tr><td rowspan="2">1st underground</td><td>Positive</td><td>2738.1</td><td>0.0025</td><td>4466.2</td><td>0.0299</td></tr>
<tr><td>Negative</td><td>2449.6</td><td>0.0025</td><td>4110.5</td><td>0.0173</td></tr>
</table>

*Notation: σ_c, σ_t and σ_{cu} are the compressive, tensile and ultimate strength of concrete in slabs, ε_c and ε_{cu} are the corresponding strain, respectively. E_s is elastic modular of steel in steel beam, σ_y and σ_{ult} are the yield strength and ultimate strength, and ε_{sh} is the strain starting to harden. F_y and F_u are the yield and ultimate strength of discrete spring elements, while S_y and S_u are the corresponding deformations. τ_{fr} is the interface friction between steel beam and concrete slab. f'_{cc} and $\alpha f'_{cc}$ are compressive strength and residual strength of confined concrete in CFST columns. σ_{sy} and σ_{st} are the yield strength and ultimate strength of steel tubes. M_{py} and M_{pu} are the yield strength and ultimate strength of the composite joints, γ_{py} and γ_{pu} are the corresponding shear deformation.

preliminarily. A lateral inverted triangle distributed load is applied on the frame. The load increases gradually, and the structure undergoes elastic, elastic-plastic stages, and failures finally.

The damage degree of the structure is identified by strains of different structural members. In this way, the structural performance in the overall loading process can be analyzed quantitatively (Asad *et al*. 2006). The value of strains identifying each damage degree considered in this paper is based on performance evaluation by strains of each response stage for frames in Asad's research. As shown in Table 2, the damage degree of the composite frame is identified by the fiber strains of cross section of beams and columns, and also the deformations of beam-to-column joints. The importance of the structural members is different for the frame. The composite joints are the most important members, and the CFST columns are more important than the composite beams. The plastic hinges are expected to appear located at the end of the composite beam. Therefore, plastic strain of beam is larger that of column to identify the same damage degree of the frame.

Table 2 Damage identifications for composite beams, CFST columns and joints

	Damage degree mark	Strain		Damage degree
		Steel	Concrete	
Composite beam	1	$\varepsilon << \varepsilon_y$	$\varepsilon << \varepsilon_c$	light
	2	$\varepsilon \leq \varepsilon_y$	$\varepsilon \leq \varepsilon_c$	light
	3	$\varepsilon_y < \varepsilon \leq 0.01$	$\varepsilon \leq \varepsilon_c$	moderate
	4	$0.01 < \varepsilon \leq 0.02$	$\varepsilon_c < \varepsilon \leq \varepsilon_{cu}$	substantial
	5	$0.02 < \varepsilon \leq 0.05$	$\varepsilon < \varepsilon_{cu}$	severe
	Damage degree	Strain		Damage degree
		Steel		
CFST column	5	$\varepsilon << \varepsilon_{sy}$	light	light
	6	$\varepsilon \leq \varepsilon_{sy}$	light	light
	7	$\varepsilon_y < \varepsilon \leq 0.005$	moderate	moderate
	8	$0.005 < \varepsilon \leq 0.01$	substantial	substantial
	9	$0.01 < \varepsilon \leq 0.02$	severe	severe
	Damage degree	Rotation		Damage degree
Connection	10	$\gamma_{py} < \gamma < \gamma_{pu}$		moderate
	11	$\gamma > \gamma_{pu}$		substantial

According to the damage degree identified method shown in Table 2, the moderate and substantial damage points of steel-concrete beams, CFST columns and composite joints are marked on the correlation curve of top lateral displacement and Total shear force by pushover analysis as shown in Fig. 3.

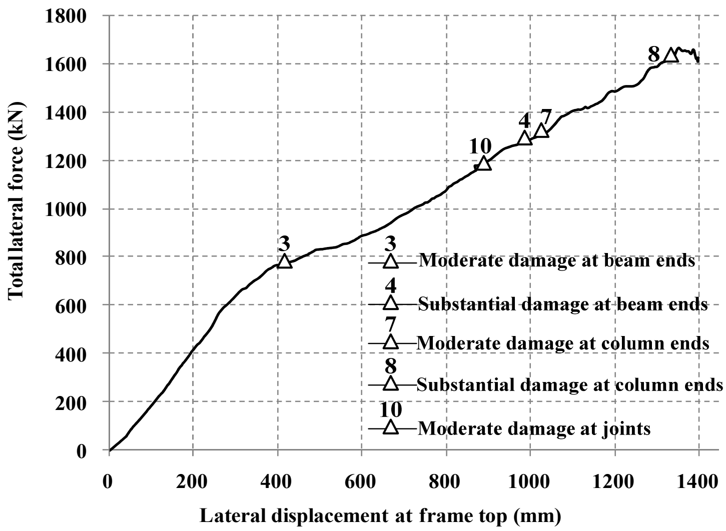


Fig. 3 The force-displacement curve and damage evolution of the composite frame

According to the results of pushover analysis, steel part of the end of composite beam located at the 1st story underground yields firstly, leading to moderate damage at beam, and the damage degree is identified as 3, as shown in Fig. 3. At this point of the curve, the total lateral force is 774 kN, and the corresponding top displacement reaches 423 mm. As the loading increases, steel part of the end of composite beam at the 2nd story underground yields when the total lateral force is 833 kN, and the corresponding top displacement reaches 504 mm. And then, the composite beam at the 3rd story underground yields when the total lateral force is 878 kN, and the corresponding top displacement reaches 589 mm. The composite beam at the 4th story underground yields when the total lateral force is 1175 kN, and the displacement reaches 884 mm. The substantial damage occurs at the end of composite beam at the 1st story underground when the total lateral force is 1264 kN, and the corresponding top displacement reaches 975 mm, and damage degree of this point is identified as 4. The steel tube of CFST column at the 4th story underground yields when the total lateral force is 1274 kN, and the corresponding top displacement reaches 1000 mm. It means that the moderate damage appears in the column, which is identified as damage 7. The substantial damage occurs at the CFST column of the 4th story underground when the total lateral force is 1535 kN, and the corresponding top displacement reaches 1606 mm, which point is identified as damage 8. The joint shear panel of the 4th story underground yields when the total lateral force is 1183 kN, and the corresponding top displacement reaches 890mm. It means that the moderate damage appears in the joint, and which is identified as damage 10.

It should be noted that damage 10 occurs before damage 4. It is discovered that the sequence of damage of structural members is unreasonable. It could result in that the collapse mechanism of the frame under the increasing lateral loads deviates from what it should be expected. In this way, the seismic capacity of the composite frame is limited, and strength of beams and columns could not be explored and utilized fully.

When the pushover finished, the damage degree of the steel-concrete composite beam ends,

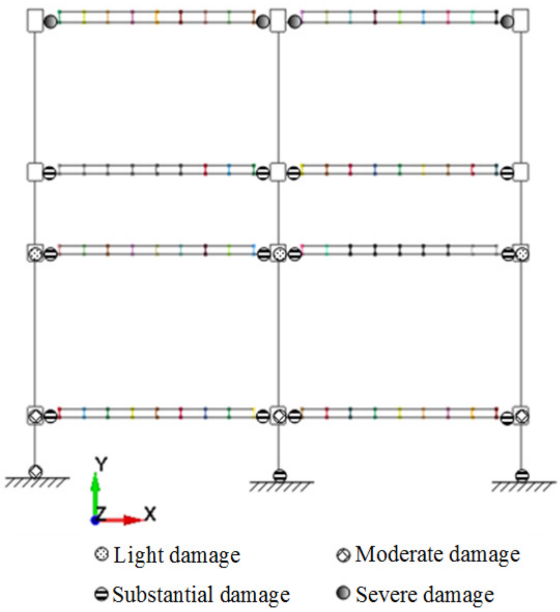
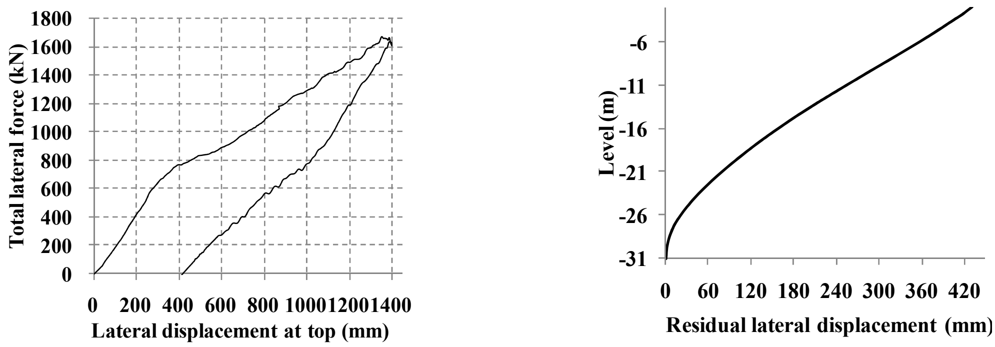


Fig. 4 The damage locations of the composite frame under lateral force



(a) Loading-unloading curve (b) Residual lateral displacement along level

Fig. 5 Loading-unloading curve and residual lateral displacement along level of the composite frame

CFST column ends and the beam-to-column joints are shown in Fig. 4. It can be seen that, thebottom story of the frame structure falls into failure. Substantial damage appears at the middle and right CFST column of the bottom story. Moderate damage appears at the beam-to-column joints of this story. As for the top story, severe damage occurs at all the composite beam ends, what result in may be the large gravity load of the overburden soil and the largest lateral push force of all the stories. However, the failures of beams are not fatal to the overall frame structure. It should be noted that yield strength of shear panel of the composite joints and steel tube of CFST columns at the bottom story should be improved significantly to reduce their damage. The joints and columns, especially those of the bottom story, are important to the overall composite frame structure.

As Fischer stated (Fischer and Victor 2003), when the plastic deformation of the column base is large in the earthquake, the structural residual deformation tends to be large. It brings about difficulties and challenges for the repair of the entire structure after the earthquake. Residual deformation is a key index to assess whether a structure can be reused or restored after an earthquake. Fig. 5(a) shows the lateral force versus displacement curve of the structure in unloading process, and Fig. 5(b) shows the residual displacement along levels when the unloading process is finished. What mainly contribute the residual lateral deformation of this composite frames are that the large plastic deformation of joints, and the yielding of steel tube of the CFST columns base at the bottom story.

2.4 Comparison with composite frames employing high strength steel

Results described in the previous section shows that steel strength influences the damage degree of the whole composite frame structure significantly. Herein, a composite frame with high strength steel is also analyzed. Zhao and Yuan (2010) conducted experimental study on the mechanical behavior of steel-concrete composite beams with high strength steel. Recent research advances of performance of high strength steel and their applications in structures was given in Shi *et al*. (2014). It was shown that high strength steel is capable of improving the seismic performance of structures.

In case of high strength composite frame, the yield strength of steel material used for steel beams of composite beam, steel tube of CFST columns and shear panel of joints is 420 MPa. Geometric dimensions of cross section of beams and columns of the high strength frame are the

Table 3 Material properties for the macro-model of the high strength composite frames

<table>
<tr><td rowspan="2">Concrete fiber in slabs</td><td colspan="2">σ_c (MPa)</td><td>ε_c</td><td>σ_{cu} (MPa)</td><td>ε_{cu}</td><td>σ_t (MPa)</td></tr>
<tr><td colspan="2">30.0</td><td>0.0022</td><td>3.0</td><td>0.0050</td><td>2.8</td></tr>
<tr><td rowspan="2">Steel fiber in steel beams</td><td colspan="2">E_s (GPa)</td><td>σ_y (MPa)</td><td>ε_{sh}</td><td>σ_{ult} (MPa)</td><td>ε_{ult}</td></tr>
<tr><td colspan="2">200</td><td>420.0</td><td>0.04</td><td>520.0</td><td>0.20</td></tr>
<tr><td rowspan="2">Spring for shear connection</td><td colspan="2">F_y (kN)</td><td>S_y (mm)</td><td>F_u (kN)</td><td>S_u (mm)</td><td>τ_{fr} (kN)</td></tr>
<tr><td colspan="2">127.5</td><td>1.0</td><td>136.5</td><td>4.8</td><td>12.8</td></tr>
<tr><td rowspan="3">Concrete fiber in CFST column</td><td colspan="2" rowspan="2">3rd and 4th underground story</td><td>f'_{cc} (MPa)</td><td>ε_{cc}</td><td>$\alpha f'_{cc}$ (MPa)</td><td>ε_{ccu}</td></tr>
<tr><td>57.3</td><td>0.0049</td><td>47.3</td><td>0.047</td></tr>
<tr><td colspan="2">1st and 2nd underground story</td><td>57.5</td><td>0.0051</td><td>47.4</td><td>0.048</td></tr>
<tr><td rowspan="2">Steel fiber in steel tubes</td><td colspan="2" rowspan="2"></td><td>σ_{sy} (MPa)</td><td>ε_{sy}</td><td>σ_{st} (MPa)</td><td>ε_{st}</td></tr>
<tr><td>454</td><td>0.0023</td><td>381</td><td>0.0019</td></tr>
<tr><td rowspan="9">Spring for beam-to-column joint</td><td colspan="2"></td><td>M_{py} (kNm)</td><td>γ_{py}</td><td>M_{pu} (kNm)</td><td>γ_{pu}</td></tr>
<tr><td rowspan="2">4th underground</td><td>Positive</td><td>3752.3</td><td>0.0031</td><td>5967.9</td><td>0.0159</td></tr>
<tr><td>Negative</td><td>3313.8</td><td>0.0031</td><td>5403.4</td><td>0.0147</td></tr>
<tr><td rowspan="2">3rd underground</td><td>Positive</td><td>3752.3</td><td>0.0031</td><td>5967.9</td><td>0.0159</td></tr>
<tr><td>Negative</td><td>3313.8</td><td>0.0031</td><td>5403.4</td><td>0.0147</td></tr>
<tr><td rowspan="2">2nd underground</td><td>Positive</td><td>2740.5</td><td>0.0031</td><td>4323.7</td><td>0.0171</td></tr>
<tr><td>Negative</td><td>2420.9</td><td>0.0031</td><td>3921.1</td><td>0.0148</td></tr>
<tr><td rowspan="2">1st underground</td><td>Positive</td><td>3145.3</td><td>0.0031</td><td>4807.1</td><td>0.0304</td></tr>
<tr><td>Negative</td><td>2800.6</td><td>0.0031</td><td>4397.0</td><td>0.0180</td></tr>
</table>

same as those of the ordinary strength frame in previous section.

The macro-model material properties computed for the pushover analysis of the high strength composite frames are listed in Table 3. It should be noted that compared with Table 1, the properties involving steel strength in Table 3 have increased compared to those of the ordinary frame, such as the yield strength and ultimate strength of steel fibers in steel beams and steel tubes, and the yield strength and ultimate strength of the composite joints. Furthermore, the compressive strength and residual strength of confined concrete fibers in CFST columns also are increased due to the enhancement of the peripheral confining steel fibers. The identification method of the damage degree of the high strength frame is also based on strains of the structural members, the same as that of the ordinary strength frame as shown in Table 2.

Fig. 6 shows the comparison of loading-unloading curves and damage evolutions of the high strength and ordinary strength composite frame. As shown in Fig. 6, in case of the high strength frame, the total lateral forces corresponding to moderate damage, substantial damage occurring at beam ends and moderate damage occurring at joints have been improved by 10%. It should be noted that no moderate and substantial damage occur at the CFST columns of the high strength frame until the pushover finished. It can be seen from the unloading curve that the residual deformation of the high strength composite frame is less than that of the ordinary strength frame notably. As for the high strength frame, steel tube of CFST columns have not yielded when unloading starts, and the plastic deformation of the structure is relatively small.

It is concluded that as for the composite frame with high strength steel, resistance of the

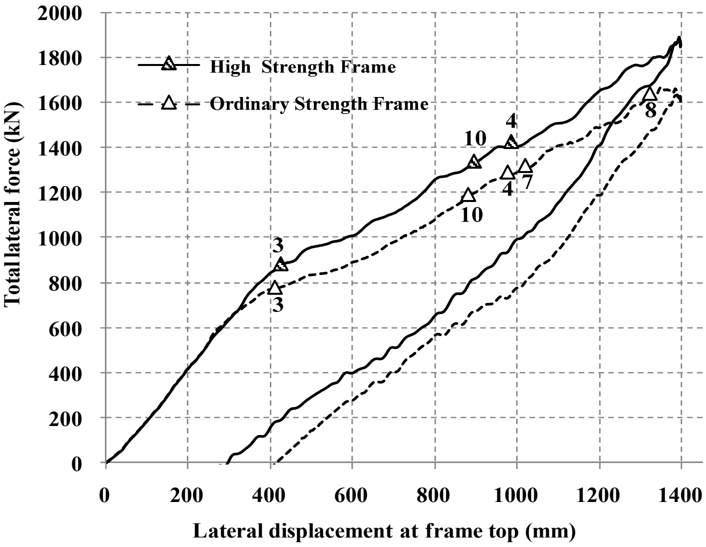


Fig. 6 The loading-unloading curve and damage evolution of the high strength and ordinary strength composite frame

structure to lateral force is improved. Under the same lateral deformation, the damage degree of the structure is lower than the ordinary strength structure. It is evidenced by that the damage degree of the ordinary strength frame is precede to that of the high strength frame by about 10 mm to 15 mm. High strength frame has favourable elasticity resuming performance, resulting in improved post-earthquake reparability.

3. Conclusions

The paper described an approach of simplified macro-modelling for composite frames consisting of steel-concrete composite beams and CFST columns, presented pushover nonlinear analysis of a 2D four-story two-bay composite frame structure based on the developed macro-modelling procedure for composite frames, and proposed the identification method of damage degree of structures based on the results of pushover analysis. According to findings from the study, the following general conclusions can be drawn:

(1) By means of the proposed damage degree identification method, the damage evolution and development of this composite frame are expressed in the whole loading process from elastic, elastic-plastic stages, to failure status. The failure mode of this composite frame is estimated as that the CFST column bases of the bottom story damage substantially resulting in that the bottom story fall to failure.

(2) It should be noted that moderate damage at joints occurs before substantial damage at beam ends. Measures should be taken to enhance the composite beam-to-column joints. Reasonable sequence of damage of structural members is beneficial for obtaining the favourable failure mechanism and seismic capacity of composite frames.

(3) Utilization of high strength steel in composite structural members improves seismic capacity and post-earthquake resuming ability of composite frames.

Acknowledgments

The author would gratitude support and financial resource from the National Natural Science Foundation of China (No. 51208292). State Key Laboratory for Hazard Reduction in Civil Engineering, the Ministry of Science and Technology of China is also gratefully acknowledged.

References

Asad, U.Q., Ye, L. and Lu, X. (2006), "Passive control reinforced concrete frame mechanism with high strength reinforcements and its potential benefits against earthquakes", *Tsinghua Sci. Technol.*, **11**(6), 640-647.

Baskar, K., Shanmugam, N. and Thevendran, V. (2002), "Finite-element analysis of steel-concrete composite plate girder", *J. Struct. Eng.*, **128**(9), 1158-1168.

El-Lobody, E. and Lam, D. (2003), "Finite element analysis of steel-concrete composite girders", *Adv. Struct. Eng.*, **6**(4), 267-281.

El-Tawil, S. and Deierlein, G. (2001), "Nonlinear analysis of mixed steel-concrete frames. I: Element formulation", *J. Struct. Eng.*, **127**(6), 647-655.

Fischer, G. and Victor, C. (2003), "Intrinsic response control of moment resisting frames utilizing advanced composite materials and structural elements", *ACI Struct. J.*, **100**(2), 166-176.

Kalkan, E. and Kunnath, S.K. (2007), "Assessment of current nonlinear static procedures for seismic evaluation of buildings", *Eng. Struct.*, **29**(3), 305-316.

Leon, R.T. and Hu, J.W. (2011), "The AISC 2010 seismic provisions for composite structures: towards an application of PBD principles for connection design", *Proceedings of the 9th Pacific Conference on Earthquake Engineering Building an Earthquake-Resilient Society*, Auckland, New Zealand, April.

Men, J., Zhang, Y. and Guo, Z. (2015), "Experimental research on seismic behavior of a composite RCS frame", *Steel Compos. Struct.*, *Int. J.*, **18**(4), 971-983.

Nie, J., Qin, K. and Cai, C. (2008), "Seismic behavior of connections composed of CFSSTCs and steel-concrete composite beams-finite element analysis", *J. Constr. Steel Res.*, **64**(6), 680-688.

Qin, Y., Chen, Z., Yang, Q. and Shang, K. (2014), "Experimental seismic behavior of through-diaphragm connections to concrete-filled rectangular steel tubular columns", *J. Constr. Steel Res.*, **93**, 32-43.

Reyes, J.C. and Chopra, A.K. (2011), "Three-dimensional modal pushover analysis of buildings subjected to two components of ground motion, including its evaluation for tall buildings", *Earthq. Eng. Struct. Dyn.*, **40**(7), 789-806.

Santoro, M.G. and Kunnath, S.K. (2013), "Damaged-based RC beam element for nonlinear structural analysis", *Eng. Struct.*, **49**, 733-742.

Shi, G., Hu, F. and Shi, Y. (2014), "Recent research advances of high strength steel structures and codification of design specification in China", *Int. J. Steel Struct.*, **14**(4), 873-887.

Valipour, H.R. and Bradford, M. (2012), "An efficient compound-element for potential progressive collapse analysis of steel frames with semi-rigid connections", *Finite Elem. Anal. Des.*, **60**, 35-48.

Zhao, H. and Yuan, Y. (2010), "Experimental studies on composite beams with high-strength steel and concrete", *Steel Compos. Struct.*, *Int. J.*, **10**(4), 297-307.

Zhao, H., Kunnath, S.K. and Yuan, Y. (2010), "Simplified nonlinear response simulation of composite steel-concrete beams and CFST columns", *Eng. Struct.*, **32**(9), 2825-2831.

Zhou, T., Jia, Y., Xu, M., Wang, X. and Chen, Z. (2015), "Experimental study on the seismic performance of L-shaped column composed of concrete-filled steel tubes frame structures", *J. Constr. Steel Res.*, **114**, 77-88.

CC