17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

NUMERICAL STUDY ON SEISMIC RETROFITTING OF RC FRAME STRUCTURES USING WING WALLS

Y. Li[(1)], Q. Zhang[(2)], J. Sun[(3)]

[(1)]Lecturer, School of Civil Engineering and Architecture, Northeast Electric Power University, Jilin China, sdlybing@hotmail.com
[(2)]Graduate Student, School of Civil Engineering and Architecture, Northeast Electric Power University, Jilin China, 1035574329@qq.com
[(3)]Graduate Student, School of Civil Engineering and Architecture, Northeast Electric Power University, Jilin China, 516685256@qq.com

Abstract

Constrained by economic conditions, technology and construction management level, the seismic capacity of building structures in developing countries is relatively weak compared with developed countries. Strong earthquakes brought greater threats and disasters to developing countries. Reinforced concrete (RC) frame is a popular structure style in the world. The main objective is to develop a practical strengthening method for substandard RC buildings with weak beam-column joints on consideration of the conditions of developing countries. Using finite element method (FEM), strengthening effectiveness for interior beam-column joint and plane frame was examined. The existing part of the specimens represented an earthquake-damaged building in 2009 Sumatra earthquake in Indonesia. Number and installed location of wing walls were also changed for the strengthened specimens. The existing frame specimens failed in joint shear. After strengthened by installing wing walls to the sides of existing columns, strength of interior beam-column joint and plane frame can be greatly increased, and the failure mode was changed from joint shear to beam yielding. Moreover, it was found that if the the amount of wing wall is sufficient, it can be installed to only one side of the columns to obtain the same strengthening objective of a beam-yielding failure mode as that when wing walls were installed to both sides of the existing columns. It is of great importance, because reducing number of wing walls means saving concrete formwork, labor, cost and construction period. This study developed a simple method to upgrade seismic performance of weak beam-column joints, especially suitable for developing countries. Moreover, the research results will reduce the difficulty of construction and accelerate construction progress, which will lay a foundation for the practical application of the method in strengthening the existing RC frame system by installing wing walls.

Keywords: Beam-column connection; Developing country; FEM; Frame structure; Retrofitting

1. Introduction

Beam-column joint plays an important role in the force transfer mechanism of a frame structure. At present, most design standards of reinforced concrete (RC) structures [1 etc.] regard beam-column joints as rigid. However, according to the past earthquake disasters, a large amount of RC buildings suffered great damages at beam-column joints, and even collapsed due to joint hinging [2-4]. The damaged beam-column joints always possess insufficient seismic capacity due to substandard structural details like those containing little or no transverse reinforcement in the joint regions. Effective and economic strengthening methods for such buildings are urgently needed.

Several studies have developed effective strengthening methods for seismic substandard beam-column joints using steel props [5], CFRP [6], etc. Li and Sanada [7] proposed a new method by installing RC wing walls beside existing columns as shown in Fig. 1. It was more suitable for developing countries in consideration of technical level, available materials, and construction cost. This method is expected to be effective for strengthening not only poorly-detailed joints but also the slender columns which commonly exist in developing countries. However, this paper only focuses on the strengthening effects for the joints by numerical simulations.

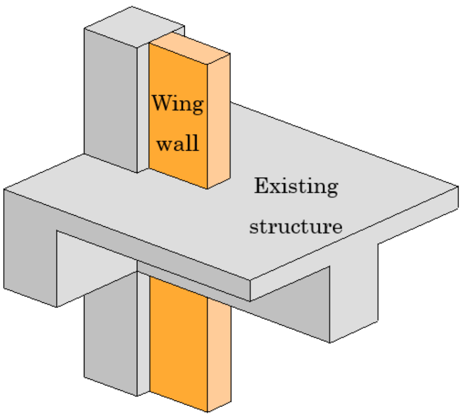


Fig. 1 - Strengthening method by installing RC wing walls proposed by Li and Sanada [7]

Past studies [7-8] validated the strengthening effectiveness for exterior beam-column joints by loading tests. However, for practical application of this method on real structures, some subjects are still left: effectiveness on other type of beam-column joints like interior ones, effectiveness on plane or space frame structures, affect of wing wall amount and location on strengthening effectiveness, etc. This study examined the strengthening effectiveness of wing wall installation method on interior beam-column joints using FEM method. Moreover, affection of wall amount and installation location were also examined.

2. Outlines of Test On Exterior Beam-Column Joints

On the 30th of September 2009, a magnitude 7.6 earthquake stroke Sumatra, Indonesia. The precious study [7] focused on an exterior beam-column joint of a three-story RC frame structure in Padang near the epicenter. This building collapsed in the earthquake, and damage was concentrated in the joints. There was no transverse reinforcement in the joints, and the hooks of beam/column shear reinforcement were 90 degrees.

Three 3/4 scale partial frame specimens modeled from the focused building were tested. One of the three specimens, designated J2, was the prototype specimen as shown in Fig.2. The other two specimens were strengthened by installing wing walls: J2-W2, in which wing wall was installed to both the upper and the lower columns, and J2-W1, in which wing wall was installed only to the lower column, as shown in Fig.3. Wing wall details were as shown in Fig.4. Reverse cyclic loading was applied to the beam tip by deformation controlling.

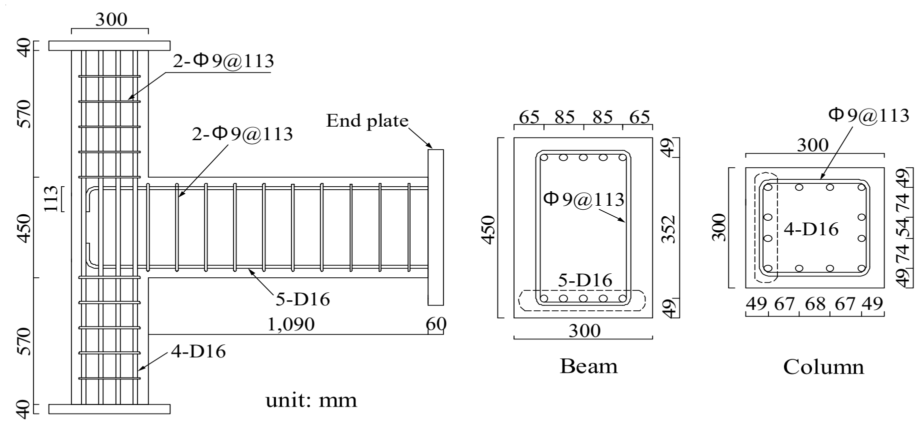


Fig. 2 - Dimensions and reinforcement details for the benchmark specimen J2 [7]

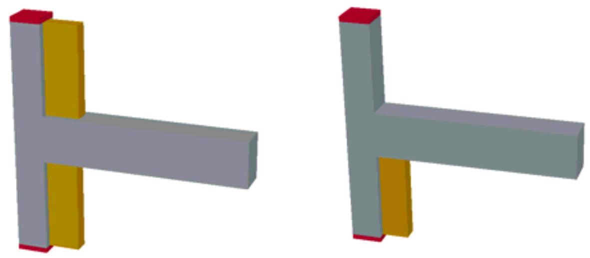


Fig. 3 - Strengthened specimens by wing wall

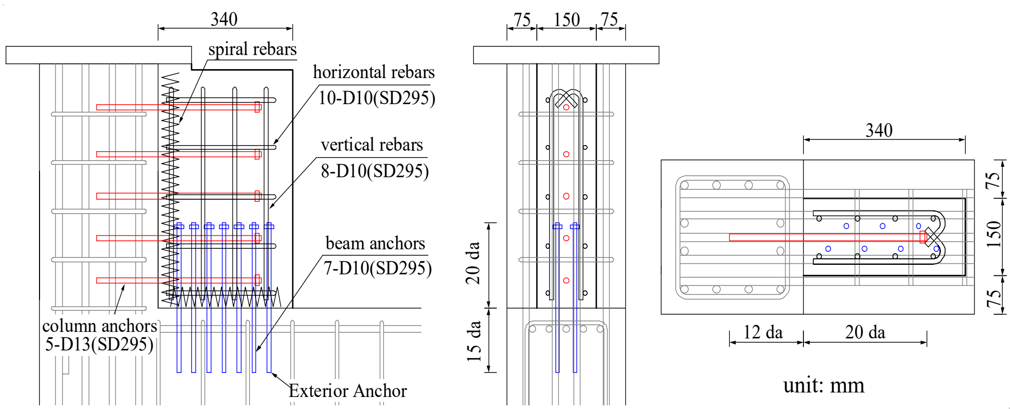
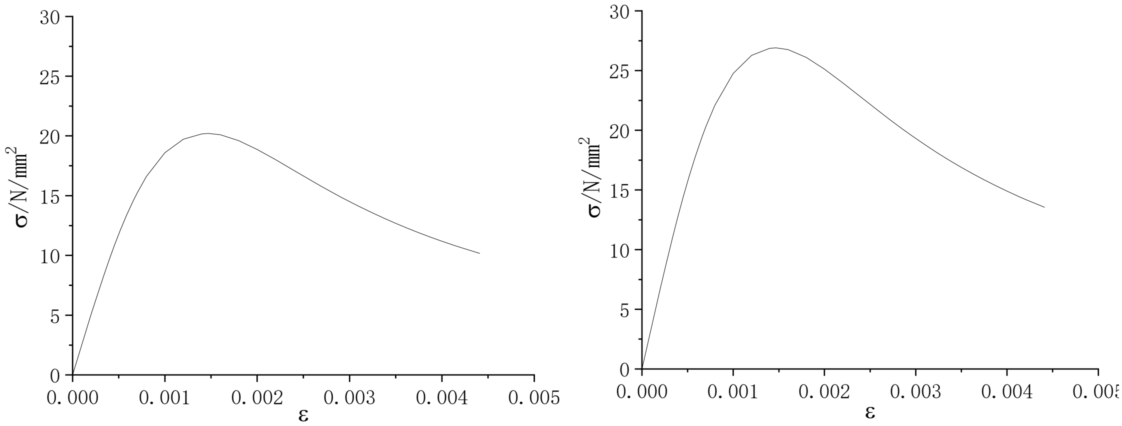


Fig. 4 - Structural details of wing wall [7]

3. Numerical Simulation on Tested Exterior Beam-column Joint Specimens

3.1 Constitutive model of materials for numerical simulation

The concrete was modeled according to the stress-strain curve provided in seismic design standard of China [9], using the tested mechanical properties in the past study [7]. The constitutive curves of concrete used in current numerical analysis are as shown in Fig.5. An ideal elasto-plastic model is used for the reinforcement. Bond-slip between concrete and reinforcement was not considered.

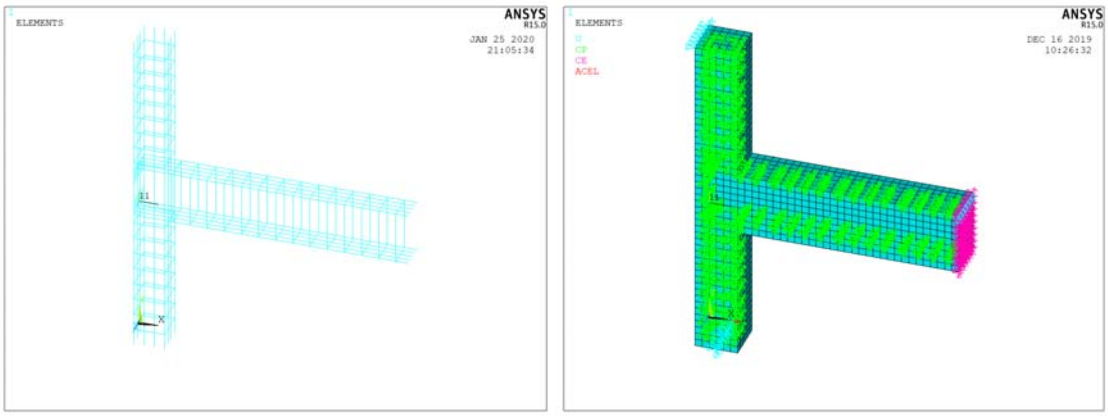


(a) Concrete for existing part (b) Concrete for wing walls

Fig. 5 - Constitution model of concrete

3.2 Finite element model

3-D finite element models were generated to simulate the tested specimens in Chapter 2. Fig.6 shows the model for the benchmark specimen, J2, as an example. For the existing frame, SOLID 65 and LINK180 elements in ANSYS were used for concrete and reinforcement, respectively. Willam-warnke five-parameter failure criterion was adopted for concrete. SOLID 65 element with reinforcement was used for concrete and rebar in wing walls, meaning that reinforcement in the wing walls was dispersed in the concrete [10]. Post installed anchors were modeled using LINK180 element. Concrete was meshed with a size of 50 mm. To avoid stress concentration, a rigid plate was arranged at tip of the columns, that is, the Young's modulus and yield stress of the plate was set to values large enough.

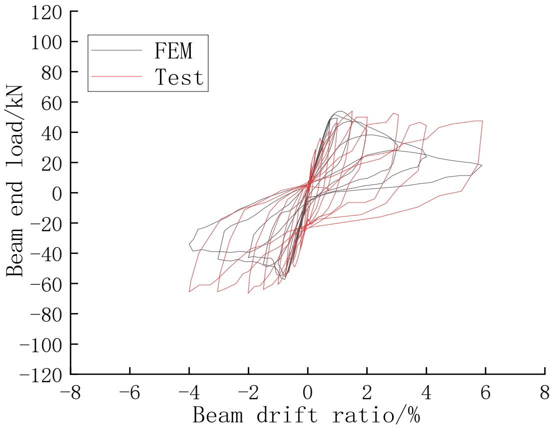


(a) Model of reinforcement (b) Meshing and boundary conditions

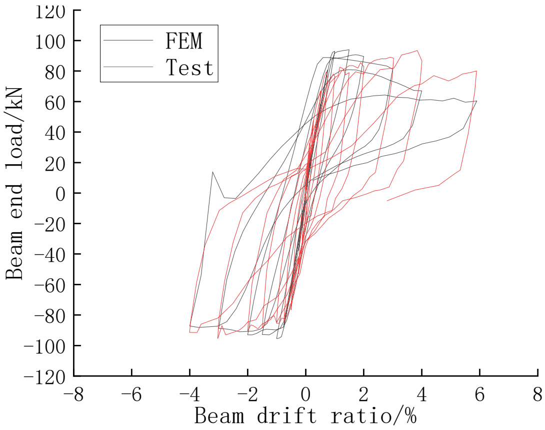
Fig. 6 - Finite element model

3.3 Comparison between numerical simulation results and test

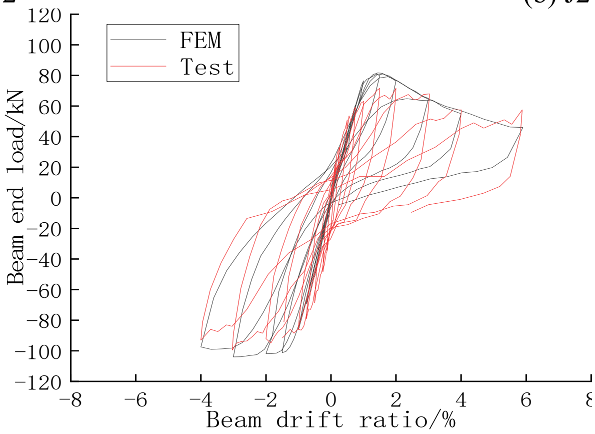
To confirm whether the FEM method is reliable or not, test and FEM analysis results were compared. Comparisons on hysteresis loops are shown in Fig.7. It was confirmed that the hysteresis loops from FEM analysis is approximately correspond with the test. The maximum strengths were also compared as shown in Table 1: errors between them were lower than 15% except for J2 in negative loading direction (16%). These results showed that the FEM model generated in this study is reasonable and can be further used in the following study. Both the numerical simulation and test validated that by installing RC wing walls, the maximum strength and energy dissipation capacity of the partial frame containing an exterior beam-column joint were largely upgraded.



(a) J2



(b) J2-W2



(c) J2-W1

Fig. 7 - Comparison on hysteresis loops from test and numerical simulation

Table 1 Comparison on maximum strengths from FEM analysis and test

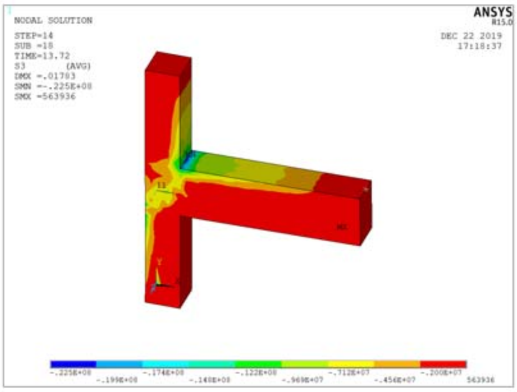
Specimen	Loading direction	Maximum strength		Error (%)
		FEM (kN)	Test (kN)	
J2	Positive	53.8	54	0.4
	Negative	-57.3	-66.5	16
J2-W2	Positive	94.1	93.5	0.6
	Negative	-95.5	-95.5	0
J2-W1	Positive	81.6	71.5	12
	Negative	-103.9	-99.5	4.2

3.4 Discussion on failure mode and strengthening effectiveness

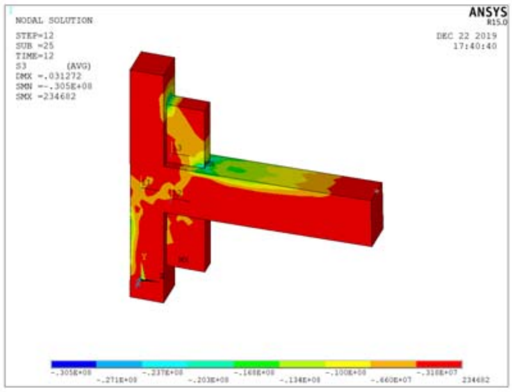
Figure 8 shows the principle compressive stress cloud chart of concrete when the maximum strengths were recorded. Table 2 shows the maximum stress together with the position of beam longitudinal reinforcement, when the maximum strength was recorded. Failure mode of the specimens and strengthening effectiveness were discussed.

3.4.1 Benchmark specimen, J2

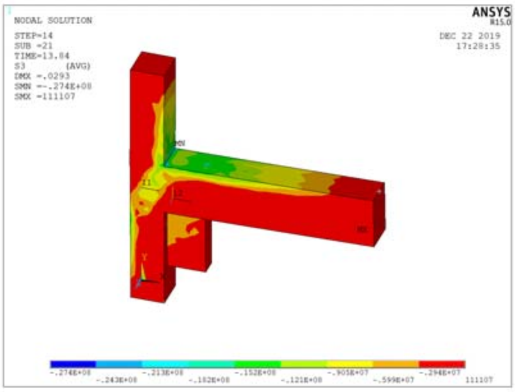
As shown in Fig.8(a), a diagonal strut was formed in the concrete at joint region of the benchmark specimen J2. The beam longitudinal reinforcement did not yield as shown in Table 2. Moreover, damage concentrated at joint and the stress of concrete at diagonal strut reached the compressive strength. These observations illustrated that the benchmark specimen failed in joint hinging.



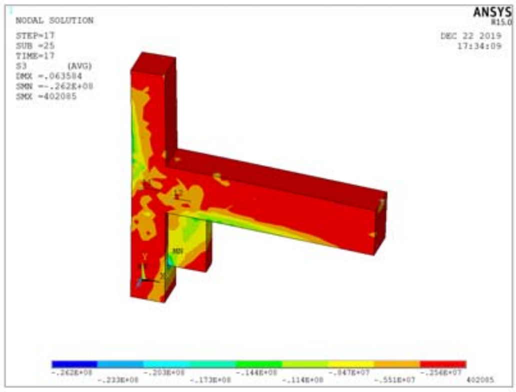
(a) J2 at positive loading



(b) J2-W2 at positive loading



(c) J2-W1 at positive loading



(d) J2-W1 at negative loading

Fig. 8 - Concrete compressive stress cloud chart of exterior beam-column joint specimens

Table 2 The maximum stress of beam longitudinal reinforcement and the measured position

Specimen	Loading direction	Beam longitudinal reinforcement	
		Maximum stress (MPa)	Position
J2	Negetive	221	Beam end (Joint face)
	Positive	208	Beam end (Joint face)
J2-W1	Negetive	373 (yielded)	Wing wall end
	Positive	370	Beam end (Joint face)
J2-W2	Negetive	373 (yielded)	Wing wall end
	Positive	373 (yielded)	Wing wall end

3.4.2 Strengthened specimen by installing two wing walls, J2-W2

As shown in Fig.8(b), by installing RC wing walls to both the upper and lower existing columns, the slop of the diagonal strut at joint (angle of strut to beam neutral axis) became smaller, connecting the compressed wall (upper wall in positive loading direction as Fig. 8b) and anchorage end of tensile beam longitudinal reinforcement. Stress of the concrete at the strut did not reach its compressive strength. A strut was also formed in the compressed wing wall, illustrating that a high compressive force was applied to the beam from the wall. Tensile stresses were observed in the post installed anchors connecting the existing beam and the tensile wing wall (the lower wall in positive loading direction as Fig. 8b). These observations supported the strengthening mechanism proposed in previous study [7] was reasonable. Both the test and numerical simulation showed that the beam longitudinal reinforcement yielded and damage concentrated in the beam at the position of wall end. These observations illustrated that a beam yielding mechanism was formed by installing wing walls to both columns.

3.4.3 Strengthened specimen by installing one wing wall, J2-W1

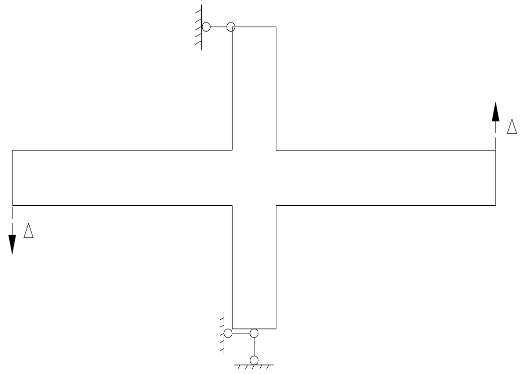
Different behaviors were observed in positive and negative loading directions. As shown in Fig.8(c), a similar diagonal strut like the benchmark specimen J2 was formed when the wing wall is pulled in positive loading direction. The tensile beam longitudinal reinforcement did not yield, although to a high level of 370 Mpa, as shown in Table 2. In negative loading direction as shown in Fig. 8(d), when wing wall was compressed, a diagonal strut was formed in the wing wall producing a large compressive force. Moreover, the stress of concrete at joint region was decreased. The beam longitudinal reinforcement yielded at the location of wall end. A similar behavior like J2-W2 was observed when the wing wall was pushed in negative loading direction. According to these observations, it was concluded that in the loading direction when wing wall was pushed as shown in Fig.8(d), a beaming yielding mechanism was formed, but not when the wall was pulled.

4. Application to Interior Beam-Column Joints

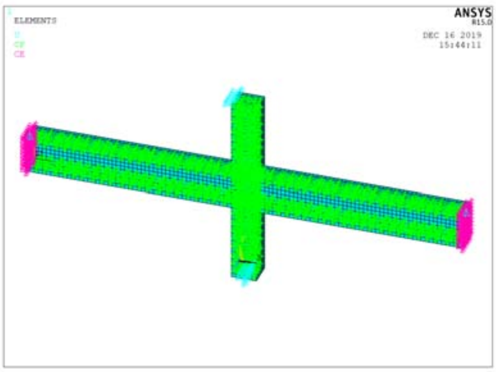
4.1 Finite element models

FEM analysis was also conducted to examine the strengthening effectiveness on interior beam-column joints. According to the same modeling rules as the exterior beam-column joint specimens in Section 3.2, three finite element models containing interior beam-column joint were established: the benchmark specimen IJ2 and the strengthened specimens designated IJ2-W2 and IJ2-W4. Dimensions, materials, and reinforcement details of the benchmark specimen were the same as the exterior joint specimens in Chapter 3, but just extending the beam longitudinal reinforcement to form a partial frame with an interior beam-column joint. Shear reinforcement was also not arranged in the joint region. Difference between IJ2-W2 and IJ2-W4 was the number of wing walls: in IJ2-W2, wing wall was installed to one side of the column (total of wing wall number is two for the upper and lower columns), and in IJ2-W4, wing walls were installed to both side of the columns (total of wall number is four).

Cyclic static loading was applied to the beam tips as shown in Fig.9(a). The loading program was the same as the exterior beam-column joint specimens. Fig.9(b) shows the finite element model of the benchmark specimen IJ2 as an example.



(a) Boundary conditions

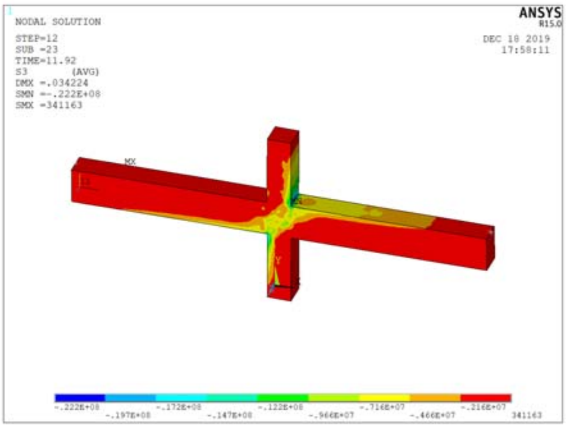


(b) Finite element model of IJ2

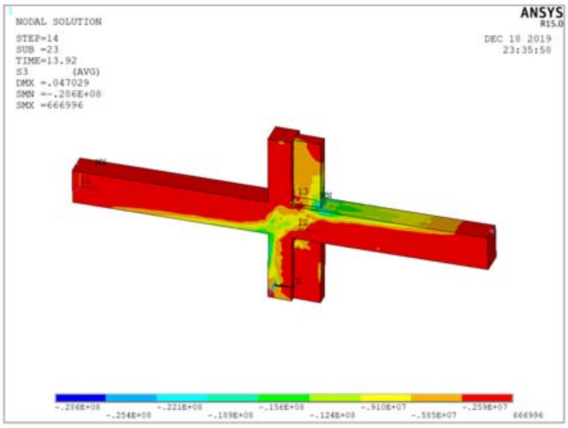
Fig. 9 - Boundary conditions and finite element model of IJ2

4.2 Damage Behavior and Failure Mode

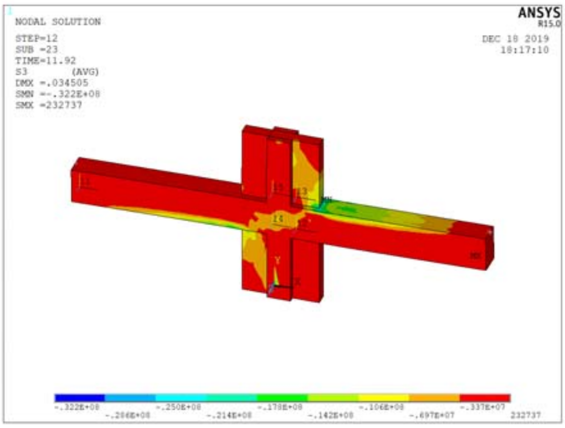
Figure 10 shows the principle compressive stress cloud chart of concrete when the maximum strengths were recorded. Fig.11 shows the specific plastic hinge distribution diagram. Table 3 summarizes the hinge location and the maximum stress of beam longitudinal reinforcement and the measured position.



(a) IJ2, positive loading

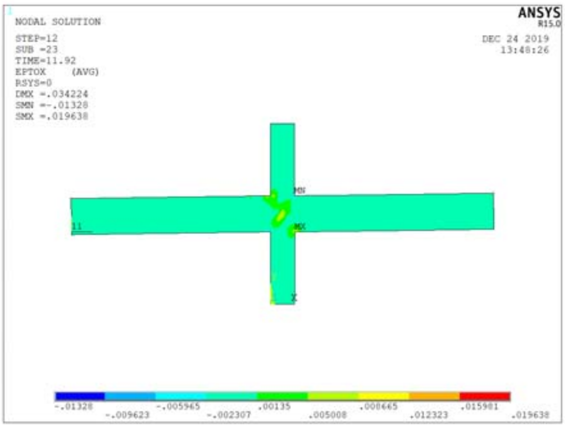


(b) IJ2-W2, positive loading

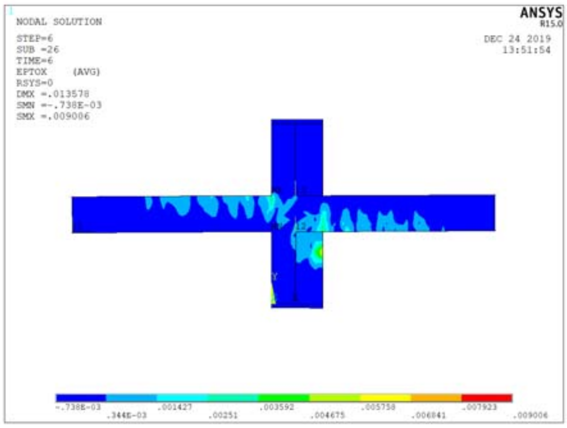


(c) IJ2-W4, positive loading

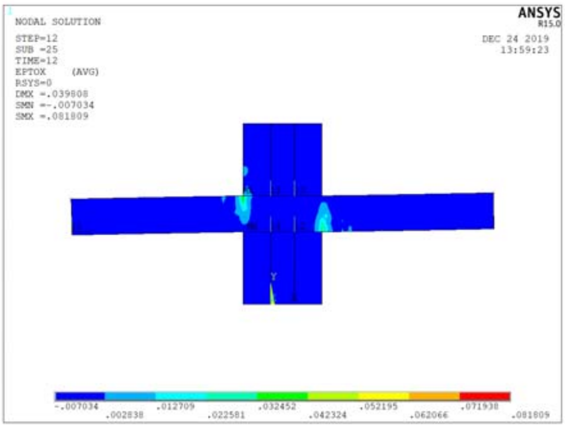
Fig. 10 - Concrete stress cloud chart at maximum strength of interior beam-column joint specimens



(a) IJ2, positive loading



(b) IJ2-W2, positive loading



(c) IJ2-W4, positive loading

Fig. 11 - Plastic hinges in specimens with interior beam-column joint

Table 3 Position of plastic hinge and maximum stress of beam longitudinal reinforcement

Specimen	Loading direction	Position of plastic hinge		Maximum stress (MPa)	Position of maximum stress	
		Left beam	Right beam		Left beam	Right beam
IJ2	Positive	Joint		338	Beam end	
	Negetive			276		
IJ2-W2	-	Beam end	Wall end	373 (yielded)	Beam end	Wall end
IJ2-W4	-	Wall end		373 (yielded)	Wall end	

4.2.1 Benchmark specimen, IJ2

Similarly to the exterior beam-column joint, a diagonal strut was also formed in the concrete at joint region, as shown in Fig.10(a). The beam longitudinal reinforcement did not yield when the maximum strength was recorded, as shown in Table 3. Plastic hinge was formed in the joint region as shown in Fig.11(a). Moreover, damage concentrated at joint and the stress of concrete at diagonal strut reached its compressive strength. These observations illustrated that the benchmark specimen failed in joint hinging.

4.2.2 Strengthened specimen by installing two wing walls, IJ2-W2

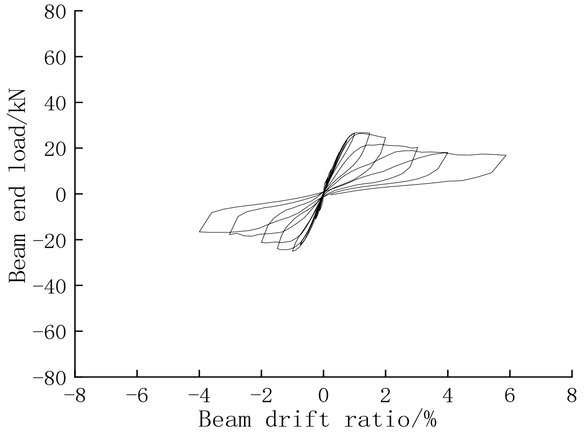
As shown in Fig.10(b), by installing RC wing walls on only one side of the columns, the slop of the diagonal strut at joint region became smaller. Stress of the concrete at the strut did not reach its compressive strength. A large compressive force was produced in the compressed wing wall and applied to the existing beam. The beam longitudinal reinforcement yielded at the wall end in the right beam and beam end (joint face) in the left beam as shown in Table 3. Moreover, plastic hinges were formed in the beams as shown in Fig.11(b). These observations illustrated that a beam yielding failure mechanism was formed by installing wing walls to one side of column.

4.2.3 Strengthened specimen by installing four wing walls, IJ2-W4

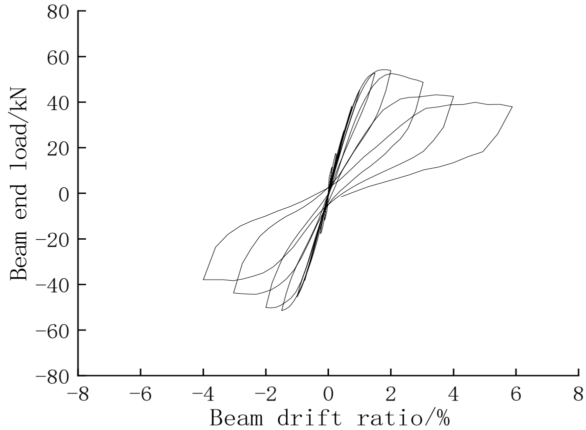
As shown in Fig.10(c), by installing RC wing walls on both sides of the columns, the slop of the diagonal strut at joint and the compressive stress of the concrete at the strut became further smaller than IJ2-W2. High compressive forces were produced in both compressed wing walls (the wall at right side of the upper column and the wall at the left side of the lower column in Fig.10c) and applied to the beam. The beam longitudinal reinforcement yielded at the beam of the end of the walls as shown in Table 3. Moreover, the plastic hinges were found clearly at the beam of the wall end as shown in Fig.11(c), illustrating that a more clear beam yielding mechanism was formed by installing wing walls to both sides of the columns.

4.3 Relationships between beam shear force and drift ratio

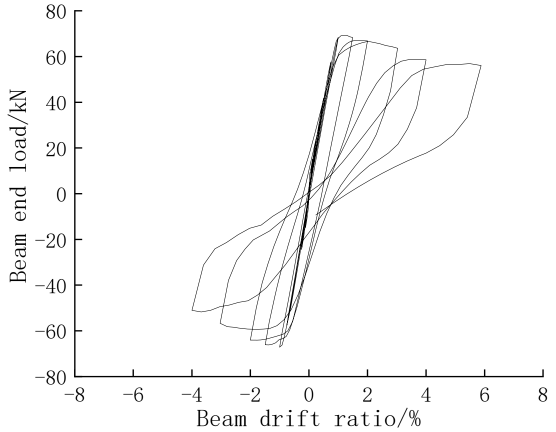
The relationships between beam shear force and drift ratio, together with their skeleton curves are shown in Fig.12. It was confirmed that comparing with the benchmark specimen IJ2, the hysteresis loops of strengthened specimens IJ2-W2 and IJ2-W4 became more full, and the energy dissipation capacity was gradually enhanced. As shown in the skeleton curves in Fig.12(d), by installing wing walls, the initial stiffness and the maximum strength was largely increased. Compared with IJ2, the maximum strength of IJ2-W2 and IJ2-W4 was increased by 103.5% and 162.8%, respectively. The strengthened specimen of IJ2-W4, in which wing walls were installed to both sides of the columns, showed better seismic behavior on maximum strength and energy dissipation than IJ2-W2, in which wing walls were installed to only one side of the columns.



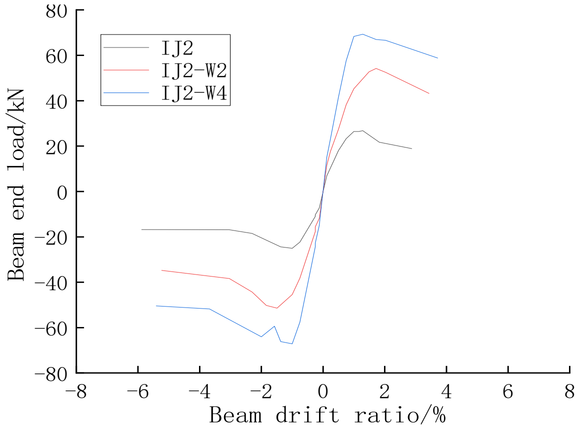
(a) Hysteresis loops of IJ2



(b) Hysteresis loops of IJ2-W2



(c) Hysteresis loops of IJ2-W4



(d) Skeleton curve of hysteresis loops

Fig. 12 - Hysteresis loops and their skeleton curves of specimens with interior beam-column joints

By installing wing walls, both IJ2-W2 and IJ2-W4 successfully achieved a beam yielding mechanism. IJ2-W4 behaved better than IJ2-W2 on seismic performance. The strengthening objective is to avoid critical joint hinging failure. In the case of this study, installing wing walls at only one side of columns also successfully achieved this objective. In practical strengthening design of interior beam-column joints, construction, cost, and space occupation of wing walls should be synthetically considered.

5. Conclusions

Past tests on strengthening of exterior beam-column joint by installing wing walls were analyzed using finite element method. In addition, the same method was applied to examine the strengthening effectiveness on interior joints. The main findings are summarized as follow.

(1) Numerical simulation based on finite element method approximately agreed with the test on specimens with exterior beam-column joint strengthened by wing walls. Large compressive forces were produced in the pushed wing wall and applied to the beam.

(2) The method of installing RC wing walls was effective on strengthening interior beam-column joints. By strengthening, joint hinging failure was avoided and a beam yielding mechanism was formed.

(3) Seismic performance of the specimen strengthened by installing wing walls to both sides of the columns behaved better than that to only one side. Installing wing walls at one side of columns could also successfully achieved the objective of avoiding critical joint failure. In practical strengthening design of interior beam-column joints, construction, cost, and space occupation of wing walls should be synthetically considered.

6. Acknowledgements

The authors are greatly thankful for the financial support of Research Foundation of The Education Department of Jilin Province (Grant: JJKH20190713KJ).

7. References

[1] National standard of People's Republic of China. Code for design of concrete structure. GB50010-2010, 2015.

[2] Sezen H, Elwood KJ, Whittaker AS, Mosalam KM, Wallace JW, Stanton JF (2000): Structural Engineering Reconnaissance of the August 17, 1999 Earthquake: Kocaeli (Izmit), Turkey, *PEER-2000/09*. Berkeley: Pacific Earthquake Research Center, University of California.

[3] Sanada Y, Kishimoto I, Kuroki M, Sakashita M., Choi H., Tani M (2009): Preliminary Report on Damage to Buildings due to the September 2 and 30, 2009 Earthquakes in Indonesia. *Proceedings of the Eleventh Taiwan-Korea-Japan Joint Seminar on Earthquake Engineering for Building Structures*, Kyoto, Japan, 297-306.

[4] Takahashi S, Sanada Y (2014): Post-Earthquake Investigation of RC Building Due to the 2013 Bohol Earthquake. *The 14th Japan Earthquake Engineering Symposium*, Chiba, Japan, 99-107.

[5] Genesio, G (2011): Seismic assessment of RC exterior beam-column joints and retrofit with haunches using post-installed anchors. Dissertation, University of Stuttgart.

[6] Gencoglu M, Mobasher B (2007): The Strengthening of the Deficient RC Exterior Beam-Column Joints Using CFRP for Seismic Excitation. International Conference on Structural Engineering, *Mechanics and Computation*, Cape Town, South Africa, 1993-1998.

[7] Li Yuebing, Sanada Yasushi (2017): Seismic strengthening of existing RC beam-column joints by wing walls. *Earthquake Engineering & Structural Dynamics*, 46(12): 1987-2008. doi: 10.1002/eqe.2890.

[8] Yuebing Li, Yasushi SANADA, Koki MAEKAWA, Haruka KATAYAMA, Ho CHOI, Kazuto MATSUKAWA, and Susumu TAKAHASHI (2019): Seismic Strengthening and Rehabilitation of RC Frame Structures with Weak Beam-Column Joints by Installing Wing Walls. *Bulletin of Earthquake Engineering*, 17(5): 2533-2567.

[9] National standard of People's Republic of China. Code for seismic design of buildings. GB50011-2010, 2010.

[10] Xinmin W (2007): ANSYS Numerical analysis of engineering structures. *China Communications Press.* 1st edition.

