SEISMIC PERFORMANCE EVALUATION OF RC COUPLING BEAMS UNDER AXIAL RESTRAINT USING MULTI-PLATFORM ANALYSIS

J. Park[(1)] and O. Kwon[(2)]

[(1)] *Postdoctoral research fellow, Department of Civil and Mineral Engineering, University of Toronto, jamin.park@utoronto.ca*

[(2)] *Associate professor, Department of Civil and Mineral Engineering, University of Toronto, os.kwon@utoronto.ca*

Abstract

In a building subjected to seismic loading, a large compressive force may develop in reinforced concrete (RC) coupling beams due to axial restraint imposed by the neighboring shear walls and expansion of the coupling beams in the failure process. The axial compressive force can increase the shear stiffness and capacity of the coupling beams and potentially change the failure mode of the coupling beams. Thus, the effect of the axial restraint needs to be taken into account for an accurate evaluation of the seismic performance of coupling beams and a structural system. In the current design practice, a building is typically modeled with linear elastic elements to reduce computational cost during design iterations. However, the linear building model cannot properly simulate the characteristic behavior of the coupling beams, as reported in previous experimental studies, such as the elongation of beam span accompanied by large compressive force acted on the beam section. On the other hand, it is not practical to model the whole building with nonlinear elements due to large computational cost and modeling time.

In this study, a new analytical procedure for evaluating the effect of the axial restraint on the seismic performance of RC coupling beams is proposed using the UT-SIM multi-platform simulation framework (www.ut-sim.ca). Target building of the analysis is an eight-story RC dual frame-wall building having 16 coupling beams. In the modeling of the building, all members other than the coupling beams, such as columns, beams, slabs, and shear walls, of which nonlinear behavior is not significant compared with the coupling beams are modeled using linear elastic beam and shell elements with S-Frame which is commercial software for structural analysis and building design. The coupling beams are modeled using nonlinear inelastic 2D-elements with VecTor2 which is specialized in nonlinear analysis of reinforced concrete members. UT-SIM Framework which has been developed in the University of Toronto is used to integrate the two numerical models and for conducting multi-platform analysis. By modeling the building using two different numerical software, the nonlinear behavior of the RC coupling beams can be more accurately simulated at low computational cost. Analysis results show that the effect of the axial restraint on shear behavior of the coupling beam cannot be ignored.

Keywords: RC coupling beam, Multiplatform analysis, Axial restraint, Seismic performance evaluation, UT-SIM framework

1. Introduction

Multistory buildings have openings that are made for architectural or practical purposes such as for accommodating elevators, stairwells, service ducts, etc. A coupling beam is used to transfer shear force between the adjacent shear walls across the openings. As the stiffness of the shear walls is much higher than that of the coupling beam, it is typically assumed that the deformation of the shear walls due to lateral forces impose equal rotation to both ends of the coupling beam, which results in a deformed shape with double-curvature with an inflection point at the mid-span.

Reinforced concrete (RC) coupling beams are often designed such that its span to depth ratio is in the range of one to two. Thus, coupling beams develop large shear deformation when a lateral force such as earthquake or wind load is applied on a building. Extensive experimental studies on the behaviour of the RC coupling beams under monotonically or cyclically applied shear force have been conducted [1]–[11]. Nevertheless, a unified analytical model for predicting the behaviour of coupling beams has not been fully established yet.

One of the main reasons in the lack of unified analytical modeling approach is that the effect of the axial restraint on the coupling beams much affect the behaviour of coupling beam. It has been reported that coupling beams elongate along their axial direction under cyclic shear loading [1], [2], [7], [12] with a magnitude increasing significantly after yielding of longitudinal reinforcement bars. Test results shows that the elongation of beam even lead to net tensile straining of all longitudinal reinforcement bars in a coupling beam [1], [7], which is quite unusual in typical RC beams. In conventionally reinforced coupling beams, the beam elongation greatly increases the pinching in their hysteretic behaviour. Also, a large shear forces applied on the beam results in the development of diagonal cracks in early stage of loading, with the crack-width increasing in proportion to the applied load. As cracks developed during one direction of the cyclic loading do not fully close when the loading direction reverses, aggregate interlocking along the crack surface reduces, thereby decreasing the area of concrete that can resist the shear force through interlocking. Accordingly, the stiffness of the coupling beam reduces considerably during the opening of the crack which leads to significant pinching and, further, significant reduction of the energy dissipation capacity of the coupling beam. Bower [13] performed numerical analysis of a coupling beam subjected to axial restraint by the neighboring shear walls by using ABAQUS (2013) and reported that the initial stiffness in axially restrained beams can increase up to two-fold compared with its unrestrained counterpart. In addition, the coupling beam with axial restraint showed considerable increase of the energy dissipation capacity. Barbachyn *et al.* [14] employed a strut-and-tie model to analytically demonstrate that the axial restraint can affect the failure mode of the coupling beam by increasing compressive stresses along the diagonal compressive strut of the coupling beam. Poudel *et al.* [8] compared the behavior of the diagonally reinforced coupling beams with/without axial restraint showing that the axial restraint can increase the strength of the coupling beam and cause buckling of diagonal reinforcements at relatively low member chord rotation.

As the elongation of coupling beams is accompanied with large compressive force due to the rotation of compressive strut under shear loading [7], it is very hard to numerically simulate this phenomenon through linear elastic analysis which is typically employed in the design of building. The axial restraint applied on coupling beams is closely related to the geometrical and structural parameters such as building height, proportion of walls in building plan, and other structural members in the building such as slabs, columns, walls, etc. Modeling the whole building using nonlinear inelastic material is ineffective considering significantly large computational time and cost it requires, which make multi-platform hybrid analysis approach more prominent in this case. By selecting critical members of which nonlinear behavior much influences the behavior of the whole building and modelling those members with nonlinear elements while modelling other members as linear elastic elements, the computational cost can be greatly reduced in association with more accurate simulation of the behavior of whole building compared with linear elastic analysis.

This study adopts the multiplatform hybrid simulation (HS) to evaluate the nonlinear behavior of the coupling beam under realistic axial restraint. To accurately consider the effect of nonlinear shear behavior of the coupling beams, all the coupling beams in a reference structure were modelled by VecTor2[15] which is a finite element (FE) software specialized in nonlinear analysis of RC members, while other members in the building were modeled as linear elastic members. Pushover analysis of the target building was performed so that the multi-platform hybrid simulation method can be validated. The analysis results show that the multi-platform hybrid simulation can effectively represent the nonlinear behavior of coupling beams under axial restraints and show characteristic behavior of a coupling beam which has been reported in previous experimental studies.

2. Multiplatform (numerical-numerical) hybrid simulation

2.1 Reference structure

The reference structure of this study is an 8-story reinforced concrete dual frame-wall building with a total height of 24 m (Fig. 1), which consists of a core of dual U-shaped shear walls facing each other and connected by two coupling beams per floor. The building is designed as an example for Eurocode 8 pre-normative provisions [16] for a peak ground acceleration of 0.15g, as a structure of high importance (level III) with medium ductility requirements and a behavior factor of 5.0. Table 1 presents cross-sectional dimensions of structural elements.

Table 1 –Member cross-sectional dimensions of target structure (unit: m)

Columns		**Shear walls b×h×thick**	**Beams**		**Slab (Waffle) b×h ribs/top fl.**
internal	**external**		**perimeter**	**coupilng**	
0.4×0.4	0.4×0.5	4.2×1.85×0.25	0.25×0.45	0.25×0.75	0.1×0.3/0.6×0.08

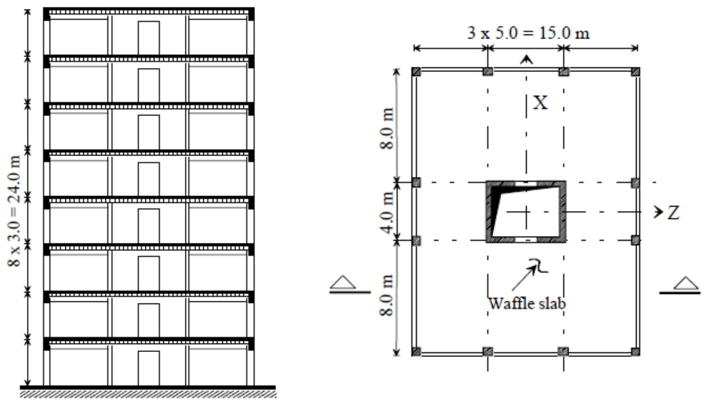

Fig. 1 – Target structure in elevation (*left*) and in plan (*right*)

A total of 16 coupling beams, two per each floor, in the target structure were originally designed with bi-diagonal reinforcement [16]. The reinforcing detail is redesigned in this study with conventional longitudinal reinforcement without diagonal reinforcement bars. The influence of the axial restraint is greater for a conventionally reinforced coupling beam than a diagonally reinforced coupling beam so that the influence of the axial restraint can be captured more clearly through the hybrid simulation. The details of redesigned coupling beam are summarized in Table 2. In the revised design, the flexural strength of the coupling beams is determined considering the double–curvature deformation mode, thereby $M_n=V_nL/2$, where M_n and V_n denote the flexural and shear strength capacities, respectively, and L is the length of the coupling beam (1.52 m).

Table 2 – Dimensions/reinforcing details of the coupling beams of target structure

Location (floor)	Dimension (mm)			Longitudinal reinforcement (area, mm²)	Stirrups		Strength	
	width	height	span		area (mm²)	spacing (mm)	flexural (kNm)	shear (kN)
2				3@D25 (1,473)		100	400	526
3				3@D28 (1,847)		75	489	641
4				3@D28 (1,847)		75	474	624
5	250	750	1520	3@D28 (1,847)	D8 (100)	90	423	557
6				3@D25 (1,473)		120	350	462
7				3@D20 (942)		150	265	349
8				3@D20 (942)		200	160	211
Roof-top				3@D20 (942)		200	91	120

2.2 FE modeling

In the multi-platform hybrid simulation, the target building was modeled into two numerically sub-structures. Considering its symmetric plan configuration, only a half of the whole building is modeled. As the nonlinear behavior of the coupling beams are greatly influence the response of whole building under cyclic shear conditions [14], [17], it is imperative that all the (eight) numerically-sub-structured coupling beams be modeled as accurately as possible. Thus, the finite element code VecTor2 [15], specialized for nonlinear analysis of RC members, was employed for modeling the coupling beams. For the other members in the target building (columns, beams and shear walls) the commercial finite element software S-Frame [18], was used. The two numerical models in VecTor2 and S-Frame are integrated through UT-SIM framework [17], [19], [20].

In the S-Frame model, all members are modeled with linear elastic elements. Beam elements were used for modeling columns and perimeter beams, while shell elements were used for slabs and shear walls. To consider the reduction of sectional stiffness of RC members due to concrete cracking, flexural and shear stiffness of beam elements was reduced based on the ASCE 41-13 guidelines [21] as shown in Table 3. Because the use of shell elements does not permit the use of reduction factors to member flexural/shear rigidity, respectively, the modulus of elasticity of the material of shell elements was reduced to 75% of that for concrete. The reduction ratio was determined such that first two eigen-frequencies from the model with shell elements are similar to those from the model of which the coupling beams are also modeled with frame elements whose stiffness were reduced based on the ASCE 41-13.

Table 3 – Reduction factors for flexural and shear stiffness of RC member

Reduction factor	Type of members			
	beam	column (According to axial force on the member section)	slab	shear wall
Flexural	0.30	0.30-0.70	0.33	0.50
Shear	0.40	0.40	0.40	0.40

In the VecTor2 model, 2D plane stress element was used for concrete while truss elements were used for reinforcement bars. Perfect bonding between the concrete and the reinforcement bars are assumed. Default material models were used for concrete and steel [15]. The properties of concrete and reinforcements used in the modelling are listed in Table 4. To model a potential crack propagation from the coupling beams to the adjacent shear walls [11], the length of each coupling beam was increased by its height. The extended part is modelled to be embedded in shear walls as illustrated in Fig. 2. To accommodate the geometry of the coupling beams, the shell elements in the S-Frame model of the shear walls is adjusted at the interface to the coupling beam.

Table 4 – Material properties of concrete and steel reinforcement

Material parameter		Value
C25/30 Concrete	Mean compressive strength (MPa)	30
	Mean tensile strength (MPa)	2.6
	Crushing strain (mm/mm)	0.0022
	Modulus of Elasticity (GPa)	31
S500 Reinforcement	Yield strength (MPa)	500
	Ultimate strength (MPa)	680
	Ultimate strain (mm/mm)	0.094
	Young's modulus (MPa)	200

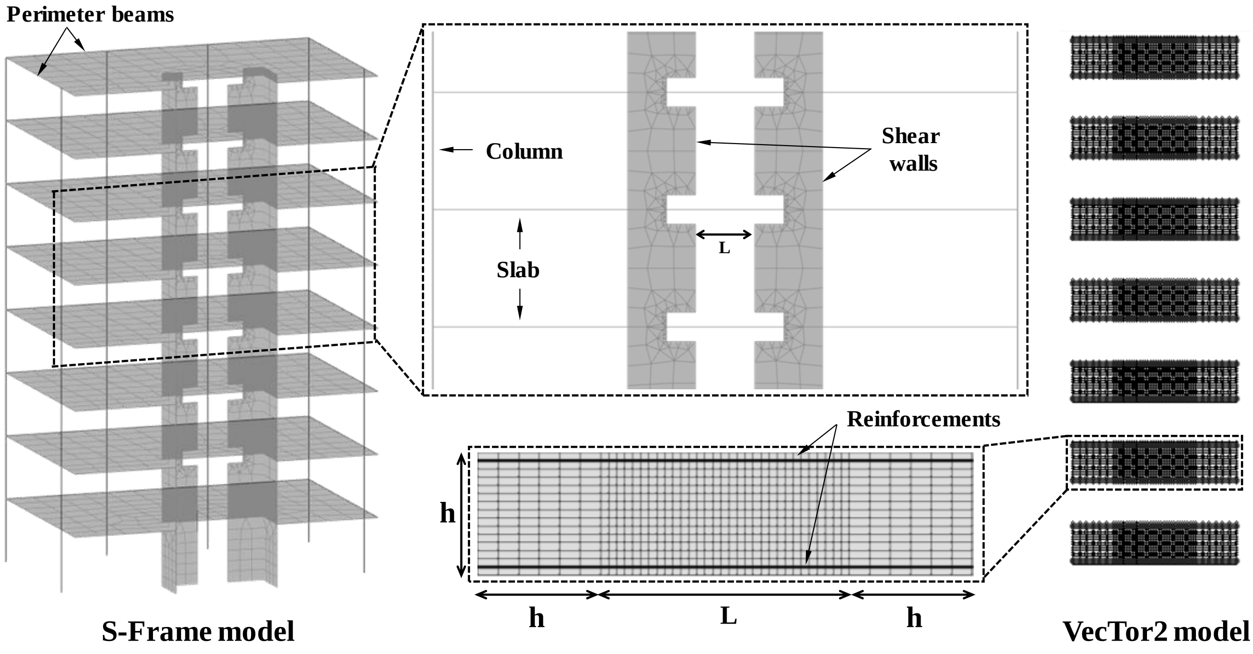

Fig. 2 – Interface node arrangement and meshing

2.3 Integration of the two numerical models for multi-platform hybrid simulation

For conducting hybrid simulation, all numerically sub-structured parts of the building need to be integrated so that compatibility of nodal displacements and equilibrium of forces are guaranteed at each analysis step among sub-structures. In this study, the S-Frame model was chosen as the one performing the nonlinear static analysis of the entire building and transferring data (target displacements) to the other substructure in VecTor2. Accordingly, interface nodes were modeled at the S-Frame model of the shear walls as shown in Fig. 3. The interface nodes were arranged along the connected boundary of the VecTor2 coupling beam models with the S-Frame shear wall model.

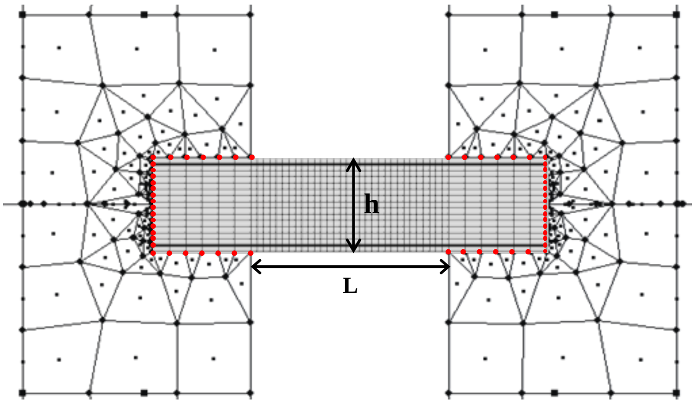

Fig. 3 – Interface node arrangement

Data exchange at interface nodes between substructures is carried out through a software library (dynamic coupling library) implemented in UT-SIM Framework, www.ut-sim.ca [22]: employing the University of Toronto Networking Protocol (UTNP), the software library provides useful functions for exchanging data between diverse numerical and experimental models [17]. The S-Frame software also provides built-in functions for communication using the UTNP at the interface nodes [20]. The schematic illustration for exchanging and processing of data during the multi-platform hybrid simulation is presented in Fig. 4.

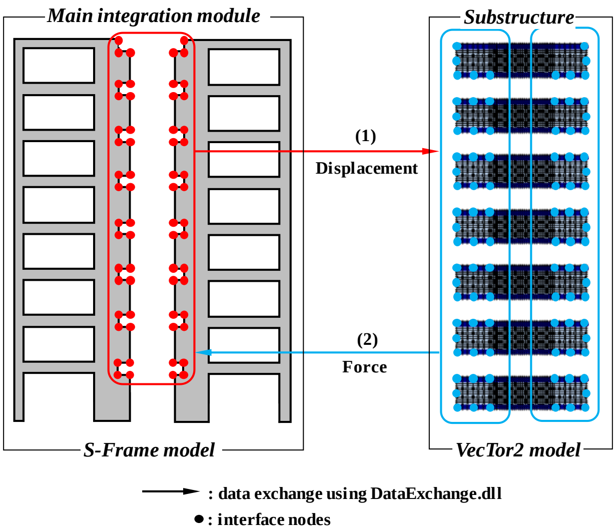

Fig. 4 – Communication between the two numerical model during hybrid simulation

2.4 Analysis program

During the multi-platform hybrid simulation, monotonic lateral load is applied to the S-Frame building model to evaluate the behavior of the coupling beams. The lateral load is modeled to be imposed on each floor as a distributed load over the entire floor area, while base shear is controlled to be monotonically increased until the base shear reaches the 2.5 times of the design base shear (2,684 kN) of the target building. For a given base shear (F_b), the load on each floor was determined per Eurocode 8 as shown in Eq. (1)

$$F_i = F_b \frac{\phi_{i1} m_i}{\sum \phi_{i1} m_i} \tag{1}$$

where, m_i denotes the *i*-th floor mass, F_i denotes the target design base shear for each step of the test, and ϕ_{i1} denotes the component of fundamental mode shape for *i*-th floor obtained by eigenvalue analysis.

In S-Frame model, the base shear was controlled to be increased through a total of 40 steps. However, as the VecTor2 conducts nonlinear analyses, the total number of analysis steps performed during hybrid simulation was 188, which includes the 4 to 6 iterations in VecTor2 for each loading step of S-Frame.

3. Analysis results and discussion

3.1 Nonlinear behavior of coupling beams under shear loading and the axial restraint

Fig. 5(a)-(d) present shear behaviour of each coupling beam and the variation of shear force, axial force, and elongation of each coupling beam, respectively. The maximum shear force of each coupling beam varies along the height. Note that the maximum shear force demands are greater than the design shear strengths of each coupling beam (see Table 2) in proportion to the level of axial force acting on each coupling beam. Fig. 5(c) shows that large compressive force develops on the coupling beams. Considering that the beam elongation is mainly due to the rotation of the diagonal compressive strut of the coupling beam [7], it is clearly shown in Fig. 5(c)-5(d) that the increase of compressive force is accompanied with the increase of the net elongation.

The net elongation is in the range of 0.10 to 0.25 % of the span of coupling beam (1,520 mm). This level of elongation is somewhat less than the observed from previous experimental studies [7], [12], which show a net elongation of greater than 2.0 %. Although the maximum shear capacity of coupling beams in VecTor2 is not attained, this is mainly due to that the coupling beams tested in those studies are not restrained in axial direction while the coupling beams analytically simulated in this study are restrained by adjacent shear walls.

Figs 6(a) and 6(b) present the deformed shape of S-Frame and VecTor2, respectively, when the maximum load is applied to the target building in S-Frame model. The influence of a nonlinear behavior of the coupling beams on the behavior of the whole building is presented in Fig. 7. In this figure, for comparison, the result of a linear elastic analysis (dashed line) is also presented where all coupling beams are modeled by linear elastic beam element of which initial stiffness is the same as the coupling beams modelled by VecTor2 in the multi-platform hybrid simulation. Though the high nonlinearity and concrete crack observed in the behavior of each coupling beam in Fig. 6(b), overall nonlinearity shown in Fig. 7 are not significant, which is mainly due to the fact that other members except for the coupling beams in the S-Frame model is modeled with linear elastic elements. Nevertheless, it can be noted that top drift increases up to 0.36 % in comparison with 0.26 % from the linear elastic analysis.

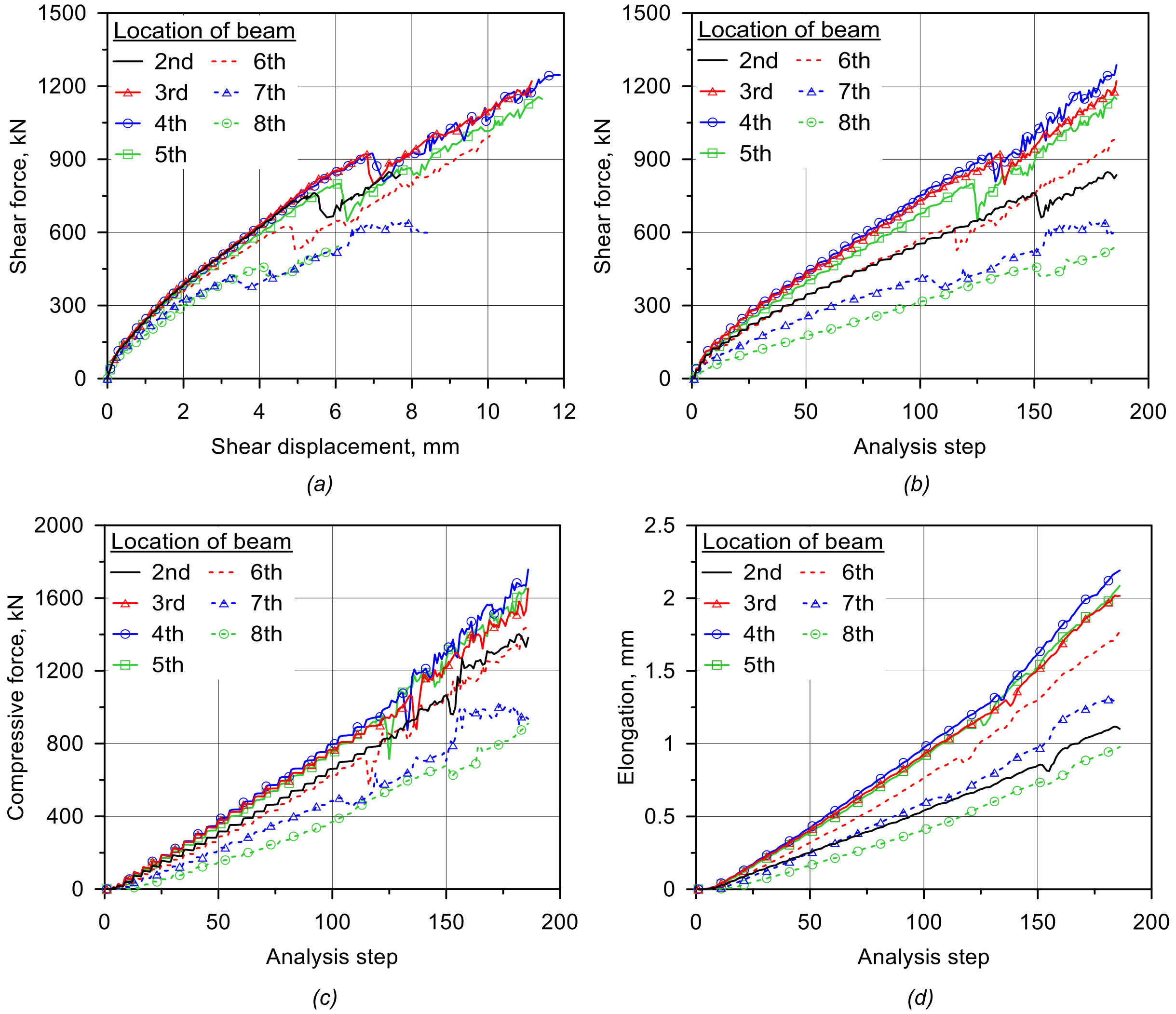

Fig. 5 – Analysis results: (a) shear force-displacement relations, (b) variation of shear force, (c) variation of compressive force, (d) variation of net elongation of beam

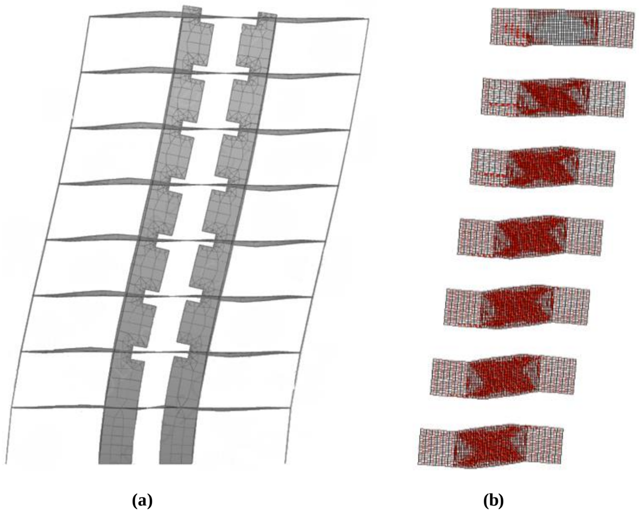

Fig. 6 – Deformation of numerical models in S-Frame and VecTor2: (a) S-Frame model, (b) Coupling beams in VecTor2 model

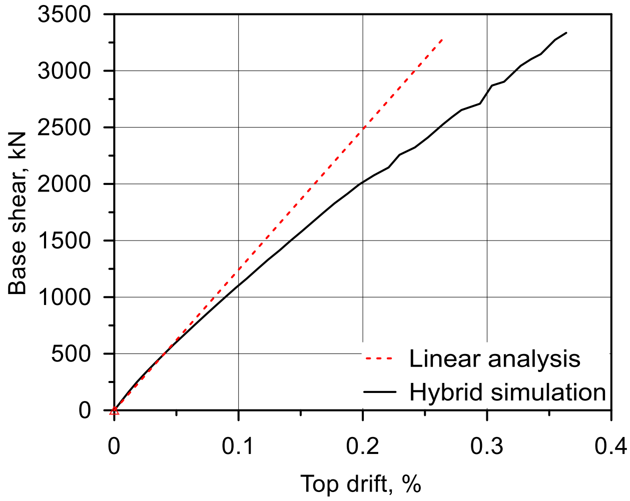

Fig. 7 – Relationship between base shear and top drift

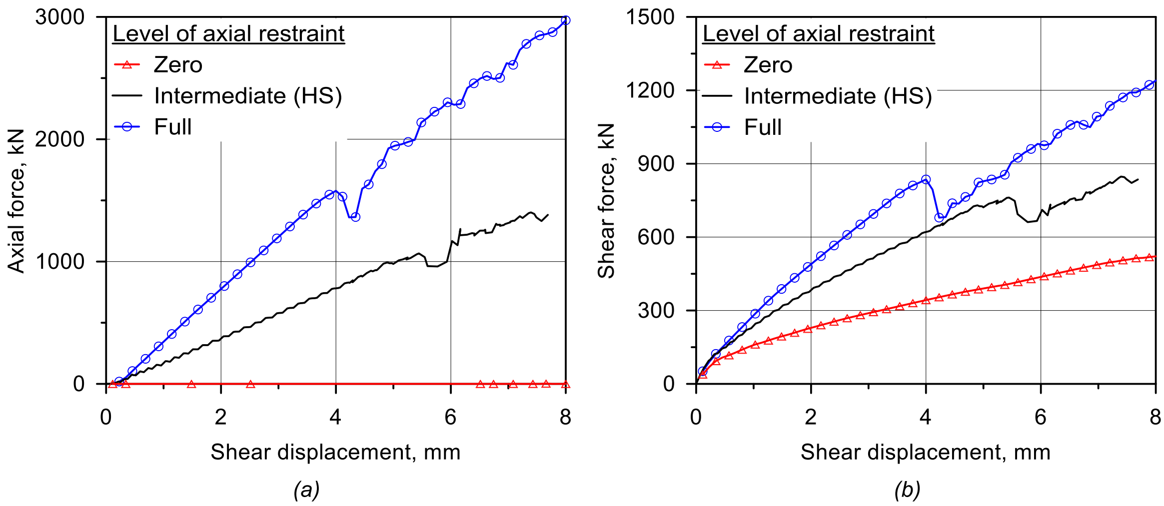

Fig. 8 – Comparison of axial and shear force of coupling beam on 2^{nd} floor depending on the level of axial restraint: (a) axial force, (b) shear force

3.2 Behaviour of coupling beam depending on the level of the axial restraint

For investigating the influence of an axial restraint imposed on the coupling beam, further analysis was performed where the level of the axial restraint is adjusted. In the analysis, the coupling beam on the 2^{nd} floor was modelled and analyzed using VecTor2 for two different levels of axial restraint: 1) zero axial restraint where the elongation of the coupling beam in axial direction can be freely occurred, 2) full axial restraint where the elongation of the coupling beam in axial direction is completely restricted. These two conditions of an axial restraint represent the two extreme levels of an axial restraint that can be imposed on the coupling beam.

Fig. 8 presents shear behavior of the coupling beam for the two axial restraint conditions in comparison with the results of the multi-platform hybrid analysis shown in Fig. 5(a). It can be noted that maximum shear force and the initial stiffness are clearly in proportion with the level of axial restraint. Accordingly, the result of the multi-platform hybrid simulation becomes an intermediate of the two extreme levels of the axial restraint. Maximum shear force for the zero axial restraint condition is similar to the design shear capacity of the 2nd floor coupling beam (526 kN) in Table 2 and the net elongation of the coupling beam was calculated as 0.8 % which is greater than the net elongation observed in the multi-platform hybrid simulation and more consistent with the large net elongation observed in previous experimental studies.

The zero axial restraints condition represents an axial restraint imposed on the coupling beam specimen from test setups which typically employed in most previous experimental studies, as summarized in [14]. Therefore, the results shown in Fig. 8 indicates that the shear capacity of coupling beams can be greatly under-estimated when the axial restraint on coupling beams are not rigorously considered during the test.

4. Conclusion

Extensive experimental research on the behavior of RC coupling beam under monotonic or cyclic shear loading has been conducted over the last decades. Those studies revealed that restraints imposed on the coupling beam in axial direction should be properly considered for evaluating the behavior of the coupling beam under shear loading. The axial restraint imposed on a coupling beam is closely related to not only the nonlinear behavioral characteristic of the coupling beam itself but the influence of other structural members in the building, especially shear walls connected to the coupling beam.

Modelling a whole building considering the nonlinear behavior of all members in the building is ineffective in that it requires impractically large computational effort. Thus, a multi-platform hybrid simulation approach was employed in this study. Accordingly, all coupling beams in a building, whose nonlinear behavior under shear loading is critical to the behavior of the building, is modelled by using VecTor2, while other members in the building are modelled by using S-Frame as linear elastic members. Pushover analysis for 8-story RC dual frame-wall building with 16 coupling beams were carried out to investigate whether the multi-platform hybrid simulation can properly simulate the nonlinear behavior of RC coupling beams depending on the level of axial restraint.

Analysis results show that shear capacity of each coupling beam is greatly increased in comparison with the design shear capacity of each coupling beam. As reported in previous experimental studies, the increase in the shear capacity is accompanied with large compressive force acting on the beam cross-section, which also resulted in elongation of the beam in the axial direction. As the nonlinear behavior of coupling beam is considered, top drift of the building is also increased in comparison with the results of a linear analysis where all coupling beams are modelled as linear elastic members. To further investigate the influence of axial restraint on the shear behavior of a coupling beam, the results of the multi-platform hybrid simulation was also compared with the behavior of coupling beam under two extreme conditions of an axial restraint that can be imposed on the coupling beam. The comparison shows that the level of an axial restraint imposed on the coupling beam in the multi-platform hybrid analysis are an intermediate of the two extreme conditions of an axial restraint.

Consequently, it can be concluded that the nonlinear behavioral characteristic of a RC coupling beam which have been reported in previous experimental research can be properly simulated by employing multi-platform hybrid simulation approach. An experimental hybrid simulation has been carried out where one of the coupling beams in the target building is experimentally considered in the lab while the other members in the structure are analytically modelled by VecTor2 and S-Frame as proposed in this paper. The experimental results are being analyzed which will be reported in a future publication.

5. Acknowledgements

The research project is funded by Collaborative Research Development Grant from Natural Sciences and Engineering Research Council of Canada. The authors acknowledge the technical supports from S-Frame to integrate S-Frame with other numerical/physical models using the UT-SIM framework.

6. References

[1] T. Paulay (1971): The Coupling of Reinforced Concrete Shear Walls. ACI Structural Journal.

[2] T. Paulay and J. R. Binney (1974): Diagonally Reinforced Coupling Beams Of Shear Walls, *ACI Spec. Publ.*, **SP 42** (26), 579–598.

[3] S. Y. Seo, H. Do Yun, and Y. S. Chun (2017): Hysteretic Behavior of Conventionally Reinforced Concrete Coupling Beams in Reinforced Concrete Coupled Shear Wall, *Int. J. Concr. Struct. Mater.*, **11** (4), 599–616.

[4] G. B. Barney, K. N. Shiu, B. G. Rabbat, A. E. Fiorato, H. G. Russell, and W. G. Corley (1980): Behavior of Coupling Beams Under Load Reversals, *Portl. Cem. Assoc.*, 1–22.

[5] T. P. Tassios, M. Moretti, and A. Bezas (1996): On the behavior and ductility of reinforced concrete coupling beams of shear walls, *ACI Struct. J.*, **93** (6), 711–720.

[6] L. Galano and A. Vignoli (2000): Seismic behavior of short coupling beams with different reinforcement layouts, *ACI Struct. J.*, **97** (6), 876–885.

[7] Z. Z. Zhao and A. K. H. Kwan (2002): Testing of coupling beams with equal end rotations maintained and local joint deformation allowed, *Proc. ICE - Struct. Build.*, **152** (1), 67–78.

[8] A. Poudel, R. D. Lequesne, and A. Lepage (2018): Diagonally Reinforced Concrete Coupling Beams: Effects of Axial Restraint.

[9] D. Naish, A. Fry, R. Klemencic, and J. Wallace (2013): Reinforced Concrete Coupling Beams — Part I: Testing, *ACI Struct. J.*, **110** (6), 1067–1075.

[10] E. Lim, S. J. Hwang, C. H. Cheng, and P. Y. Lin (2016): Cyclic tests of reinforced concrete coupling beam with intermediate span-depth ratio, *ACI Struct. J.*, **113** (3), 515–524.

[11] A. W. Fisher, E. C. Bentz, and M. P. Collins (2017): Response of heavily reinforced high-strength concrete coupling beams, *ACI Struct. J.*, **114** (6), 1483–1494.

[12] Y. Xiao, A. Esmaeily-Ghasemabadi, and H. Wu (1999): High-strength concrete short beams subjected to cyclic shear, *ACI Struct. J.*, **96** (3), 392–399.

[13] O. J. Bower (2008): Analytical investigation into the effect of axial restraint on the stiffness and ductility of diagonally reinforced concrete coupling beams. .

[14] S. M. Barbachyn, Y. C. Kurama, and L. C. Novak (2012): Analytical evaluation of diagonally reinforced concrete coupling beams under lateral loads, *ACI Struct. J.*, **109** (4), 497–507.

[15] P. S. Wong, F. J. Vecchio, and H. Trommels (2013): *VecTor2 & FormWorks User's Manual 2nd Edition*. 2013.

[16] M. N. Fardis (1994): Analysis and design of reinforced concrete buildings according to Eurocodes 2 and 8.

[17] X. Huang, V. Sadeghian, F. Rong, O. Kwon, and F. Vecchio (2017): An integrated simulation method for performance-based assessment of a structure, *6th Int. Conf. Eng. Mech. Mater.*, 1–10.

[18] S-FRAME Software Inc. (2013): *S-FRAME and S-STEEL R11.0 Reference Manual*. 2013.

[19] V. Sadeghian, O. Kwon, and F. Vecchio (2019): A framework for multi-platform simulation of reinforced concrete structures, *Eng. Struct.*, **181** (November 2018), 260–270.

[20] P. Mortazavi, X. Huang, O.-S. Kwon, and C. Christopoulos (2017): Example Manual for University of Toronto Simulation (UT-SIM) Framework 2nd Edition.

[21] American Society of Civil Engineers (ASCE) (2013): *ASCE 41-13: Seismic Evaluation and Upgrade of Existing*. American Society of Civil Engineers (ASCE), 2013.

[22] X. Huang, V. Sadeghian, and O. S. Kwon (2015): Development of integrated framework for distributed multi-platform simulation, *6AESE/11ANCRiSST.*

