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Effect of Interior Brick-infill Partitions on the Progressive Collapse Potential of a RC Building: Linear Static Analysis Results

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***Abstract*—**Interior brick-infill partitions are usually considered as non-structural components, and only their weight is accounted for in practical structural design. In this study, the brick-infill panels are simulated by compression struts to clarify their effect on the progressive collapse potential of an earthquake-resistant RC building. Three-dimensional finite element models are constructed for the RC building subjected to sudden column loss. Linear static analyses are conducted to investigate the variation of demand-to-capacity ratio (DCR) of beam-end moment and the axial force variation of the beams adjacent to the removed column. Study results indicate that the brick-infill effect depends on their location with respect to the removed column. As they are filled in a structural bay with a shorter span adjacent to the column-removed line, more significant reduction of DCR may be achieved. However, under certain conditions, the brick infill may increase the axial tension of the two-span beam bridging the removed column.

***Keywords*—**Progressive collapse, brick-infill partition, compression strut.

I. Introduction

PROGRESSIVE collapse is referred to the phenomenon of widespread propagation of structural failure initiated by local damage. Many practicing engineers and academic researchers have been engaged in the prevention of progressive collapse since the partial collapse of the Ronan Point apartment building in 1968. Resistance of building structures to progressive collapse has been an important task for the development of structural design codes. Linear static, nonlinear static, linear dynamic, and nonlinear dynamic methods are four basic approaches for the progressive collapse analysis. Advantages and disadvantages of these approaches have been discussed by Marjanishvili and Agnew [1]. Detailed descriptions of a step-by-step, linear static procedure for progressive collapse analysis have been issued by the US General Service Administration (GSA) [2] and Department of Defense (DoD) [3]. Several studies regarding the progressive collapse potential of RC or steel frames have performed recently [4]-[7]. In general, the effect of the non-structural brick-infill partitions on the progressive collapse potential is seldom considered. Sasani [8] has conducted field test to investigate the dynamic response of a RC building with brick-infill panels subjected to sudden column loss. The brick wall was modeled by shell or equivalent compression-strut elements and the simulation results were compared. For conventional RC buildings, the brick-infill panels are usually adopted for interior partitions. They are often considered as non-structural elements and only their weight is accounted for in structural design. However, from several experimental studies on brick-infill RC frames, it was observed that the brick wall may contribute to the horizontal seismic resistance of RC frames. Hence, it may help to reduce the progressive collapse potential for RC buildings.

In this paper, the GSA linear static analysis procedure is used to evaluate the effect of brick-infill panels on the progressive collapse potential of a RC building. Three dimensional finite element models of the RC building with or without brick infill are constructed. Four different column loss conditions with a total of fourteen different brick-infill locations are considered to investigate the effect of the brick-infill partition on the progressive collapse potential of the RC building.

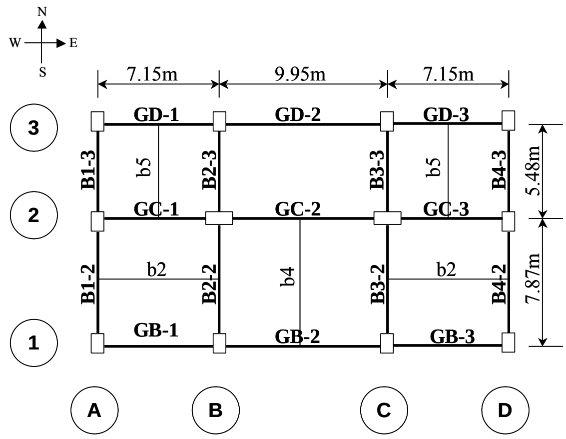

Fig. 1 Plan dimensions of the building

II. Modeling of the RC building frame

The RC building is a 10-story, moment-resisting frame structure with a 2-story basement. Its first story is an open space for the public. As shown in Fig. 1, there are three bays with

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center-to-center span length arranged as 7.15m, 9.95m, and 7.15m in the longitudinal (west-east) direction, and two bays with a 5.48m and a 7.87m span in the transverse (north-south) direction. The story height is 4m for the first story and 3.3m for the others. In addition to the self weight, a dead load (DL) of 0.98kN/m^2 is applied to the roof and 0.245kN/m^2 to other floors. The service live load (LL) is 4.91kN/m^2 for the roof and 1.96kN/m^2 for other floors. Table 1 presents the section dimensions of the RC members for the building. A compressive strength equal to 27500kN/m^2 is used for the concrete. The design yield strength is 412000kN/m^2 for the main reinforcements and 275000kN/m^2 for the stirrups.

TABLE 1 SECTION DIMENSIONS OF THE RC MEMBERS

Floor	Column	Peripheral beam	Interior beam	Joist
1F	70×100	60×90	50×90	30×65
2F	70×100, 70×90	60×75	50×75	30×65
3~4F	70×90	60×75	50×75	30×65
5~10F	70×90	50×75	50×75	30×65

The building is located at a soft soil site and its design spectral response acceleration, S_{aD}, is equal to 0.45g. All the beams and columns are designed and detailed according to seismic code requirements. Also, sum of the nominal flexural strengths of the columns framing into a joint is at least 1.2 times larger than that of the beams framing into the joint. Hence, a strong column-weak beam mechanism may be ensured. A beam-column frame model is constructed for the RC building using the SAP2000 commercial program [9]. It is assumed that the model is fixed on the ground. Self weight of the exterior walls is distributed to the spandrel beams. Also, self weight of the interior walls and partitions is estimated and applied to the floor slab as a distributed load. Thereafter, according to the tributary area, self weight of the slab and all the dead loads and live load on it are distributed to the beam elements for each floor. The fundamental period of the building model is equal to 1.48 and 1.40 seconds in the longitudinal and transverse direction, respectively.

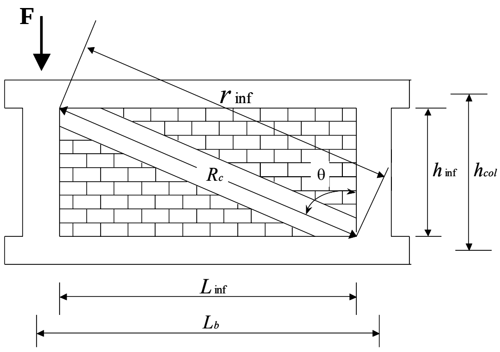

Fig. 2 Loading direction of the brick wall

III. MODELING OF THE BRICK INFILL

From several studies of brick-infill RC frames subjected to horizontal loading, the brick infill panels are usually modeled by compression-strut elements [10]-[13]. Hence, the brick-infill wall is simulated by the compression-strut model suggested by the FEMA 356 [13]. In FEMA 356, the strut model is constructed based on the horizontal seismic behavior of RC frames with brick infill. Instead, a vertical downward loading is imposed on the brick-wall panel as the building is subjected to sudden column loss, as shown in Fig.2. Therefore, the equivalent width of the compression strut, a, is modified as

$$a = 0.175(\lambda_1 L_b)^{-0.4} r_{inf}\ ,\ \lambda_1 = \left[\frac{E_{me} t_{inf} \sin 2\theta}{4E_{fe} I_b L_{inf}}\right]^{\frac{1}{4}} \tag{1}$$

where L_b and r_{inf} are the beam length between centerlines of columns and the diagonal length of infill panel, respectively. t_{inf} is the thickness of infill panel and strut. L_{inf} and E_{me} are respectively the horizontal length and expected elastic modulus of infill panel. E_{fe} is the expected elastic modulus of frame material. I_b is the moment of inertia of beam. θ is the angle whose tangent is the infill length-to-height aspect ratio in radian. As recommended by FEMA 356, E_{me} is calculated as $550 f_m'$, where f_m' is the compressive strength of the infill and assumed as 4142kPa in this study. Therefore, the elastic modulus of the infill panel E_{me} is 2278kPa. The vertical stiffness component, k_v, provided by the strut may be expressed as

$$\frac{k_v}{E_{me} t_{inf}} = 0.175(\lambda_1 L_b)^{-0.4} \left(\frac{h_{inf}}{r_{inf}}\right)^2\ ,\ \lambda_1 = \left[\frac{E_{me} t_{inf} h_{inf}}{2E_{fe} I_b r_{inf}^2}\right]^{\frac{1}{4}} \tag{2}$$

In addition, compression failure mode is assumed for the strut [14]-[15]. As recommended by FEMA 306 [15], the axial compressive strength of the strut, R_c, is expressed as

$$R_c = a t_{inf} f'_{me90} \tag{3}$$

where f'_{me90} is the horizontal expected strength of infill panel and calculated as 50% f'_{me}. f'_{me} is the expected compressive strength of test brick prism and estimated as $1.3 f_m'$. The axial compressive strength is used to assess the failure of the equivalent strut.

IV. PROGRESSIVE COLLAPSE ANALYSIS

A. Column loss conditions

Four threat-independent, column-removed conditions, designated as Case 1B, Case 2A, Case 1A, and Case 2B, are considered for the building. According to the bay line numbers in Fig. 1, the removed column of the first story is 1B, 2A, 1A, and 2B for Case 1B, 2A, 1A, and 2B, respectively. A loading combination of 2(DL+0.25LL) is applied to the adjacent bays of the removed column. The imposed loading on the rest bays of the building is (DL+0.25LL). For each column-removed condition, except the ground floor, the brick-infill panel may be filled in every story of an interior structural bay adjacent to the removed column or between the floor joists orthogonal to the structural bay. Fourteen different arrangements are considered to investigate the effect of brick-infill location, as shown in Figs. 3(a) to 3(d), where each dash lines indicate an analysis case. Numbering of each brick infill is given by its corresponding beam or joist number. The designation of analysis cases with brick infill is provided by a combination of the column-removed case and the brick-infill numbering. Because of the open space requirement, no brick infill is provided in the first story.

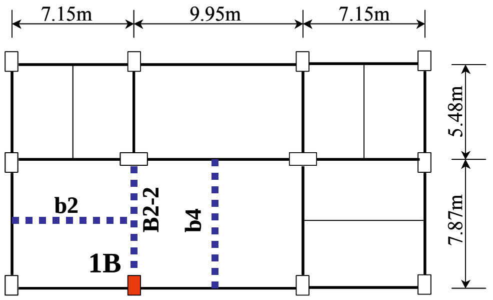

Fig. 3(a) Location of brick infill in Case 1B

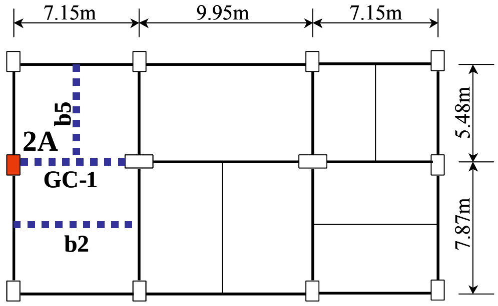

Fig.3(b) Location of brick infill in Case 2A

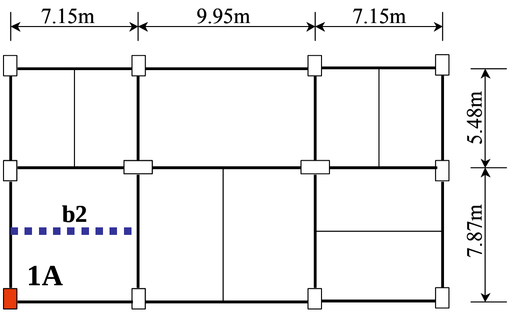

Fig.3(c) Location of brick infill in Case 1A

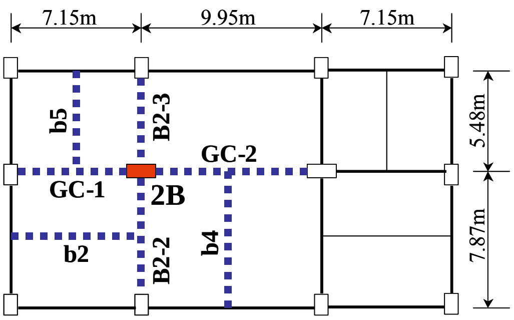

Fig. 3(d) Location of brick infill in Case 2B

B. Properties of the compression strut

As mentioned in the earlier section, each infill panel is simulated by using two diagonal compression struts. Table 2 presents the mechanical properties of the strut for each case. In order to verify the accuracy of the modified estimation for the equivalent width, the brick-infill panels are also modeled by shell elements on the other hand. Table 3 compares the fundamental period in the longitudinal direction of the brick infill for each column-removed condition. It is seen that, in general, both the strut and shell element models have approximate fundamental periods. The fundamental period of the column-removed RC building is not significantly reduced by the added brick infill. Since the brick infill may not be simulated as compression-only by using the shell element in the program [9], the compression strut model is adopted instead.

TABLE II PROPERTIES OF THE EQUIVALENT COMPRESSION STRUTS

Location	GC-1	GC-2	B2-2	B2-3	b2	b4	b5
θ [a]	68.12	74.26	70.17	61.42	67.35	69.45	60.48
k (kN/m)	32560	30372	31833	34688	29646	28812	31333
a (m)	0.82	1.05	0.88	0.68	0.75	0.8	0.62
R_c (kN)	264	338	284	218	241	258	200

a: unit in degree, k: axial stiffness of the strut

TABLE III COMPARISON OF FUNDAMENTAL PERIODS (UNIT:S)

RC frame				
Case	1B	1A	2A	2B
East-west	1.50	1.55	1.51	1.49
North-south	1.44	1.43	1.42	1.41
RC frame with brick infill				
Case	1B-B2-2	1B-b2	1B-b4	1A-b2
Strut	1.41	1.48	1.41	1.54
Shell	1.37	1.45	1.37	1.52
Case	2A-GC-1	2A-b2	2A-b5	2B-GC-11
Strut	1.48	1.48	1.39	1.45
Shell	1.44	1.44	1.37	1.38
Case	2B-GC-2	2B-B2-2	2B-B2-3	2B-b2
Strut	1.42	1.36	1.39	1.45
Shell	1.26	1.29	1.36	1.39
Case	2B-b4	2B-b5		
Strut	1.37	1.39		
Shell	1.31	1.37		

C. Analysis results

Linear static analysis is carried out to investigate the column failure responses of the building. Most of the downward loading originally sustained by the failed column is transferred to the plane frames intersecting at the line of the failed column. Therefore, the flexural demand-to-capacity ratio (DCR) of beam-ends of the adjacent bays to the removed column and the deflection of the column-removed point are the major concerns in this paper. Table 4 lists the maximum DCR, numbers of beam end with $DCR \geq 1.0$, mean DCR and displacement of the column-removed point. The mean DCR is obtained from averaging those $DCR \geq 1.0$ values. Plastic hinge may be generated at a beam end with $DCR \geq 1.0$. Difference between the maximum and the mean DCR may be used to evaluate whether the possible damage is localized at some certain frame elements. It is observed that the largest DCR (1.77) occurs in Case 2B, while Case 1B has the greatest numbers of $DCR \geq 1.0$ and largest displacement. Case 2A is less susceptible to progressive collapse than the others. With consideration of the brick-infill panels, the numbers of beam end with $DCR \geq 1.0$ and maximum DCR are generally reduced. However, the amount of reduction is dependent on the location of brick infill. More significant reduction is observed for Case 1B-B2-2 and Case 2B-B2-3 as compared to Case 1B and Case 2B, respectively.

TABLE IV ANALYSIS RESULT SUMMARY

Case	No. of $DCR \geq 1.0$	DCR_{max}	$(DCR \geq 1.0)_{mean}$	Displacement (cm)
1A	6	1.26	1.11	3.20
1A-b2	4	1.20	1.11	3.12
2A	0	0.95	0	1.72
2A-GC-1	0	0.91	0	1.66
2A-b2	0	0.95	0	1.71
2A-b5	0	0.93	0	1.69
1B	29	1.71	1.17	3.99
1B-B2-2	18	1.59	1.09	3.75
1B-b2	23	1.63	1.10	3.87
1B-b4	25	1.68	1.17	3.94
2B	20	1.77	1.21	2.58
2B-GC-1	16	1.66	1.17	2.44
2B-GC-2	17	1.69	1.18	2.47
2B-B2-2	17	1.67	1.20	2.41
2B-B2-3	10	1.59	1.16	2.41
2B-b2	18	1.74	1.20	2.54
2B-b4	18	1.74	1.22	2.53
2B-b5	18	1.73	1.19	2.54

Figs.4(a)~4(e) show the story mean DCRs of the adjacent bays to the removed column for each analysis case. It is seen that the contribution of brick infill to reducing the flexural demand in every story is quite uniform for this RC building. The first story with column removal usually has the largest DCR demand. In general, the brick-infill panels filled in a structural bay adjacent to the removed column may perform better than that filled in between the joists connected to the structural bay. Also, the shorter the brick wall, the better the flexural demand reduction. This arises from the fact that the vertical stiffness component of the compression strut increases with decreasing wall length. Among the four column-removed conditions, Case 2A has the smallest DCRs in average and reveals elastic response under the 2(DL+0.25LL) loading. Therefore, effect of the brick infill GC-1 in Case 2A on distributing the downward loading is less significant than that of the B2-2 in Case 1B. Since the brick-infill panels filled in between the joists do not directly intersect with the removed-column line, their load-transfer function is limited.

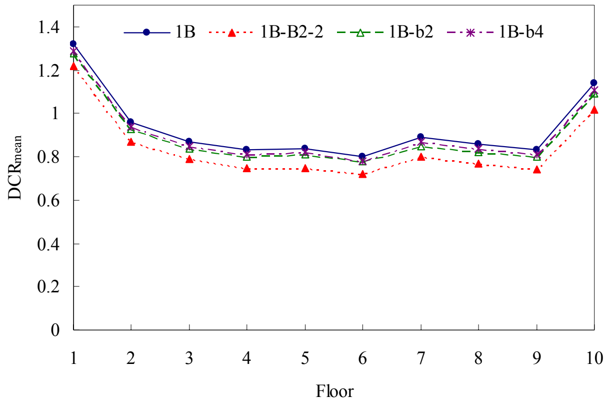

Fig. 4(a) Mean DCRs for Case 1B

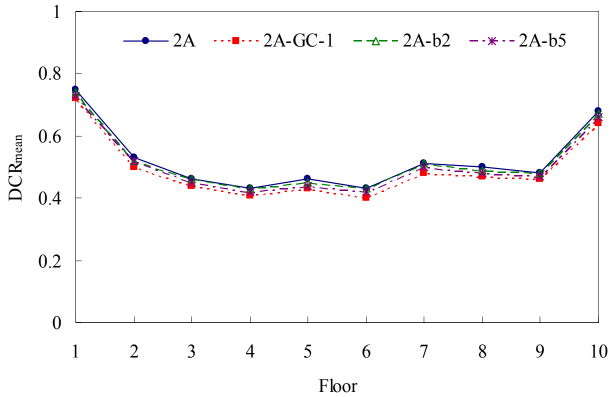

Fig. 4(b) Mean DCRs for Case 2A

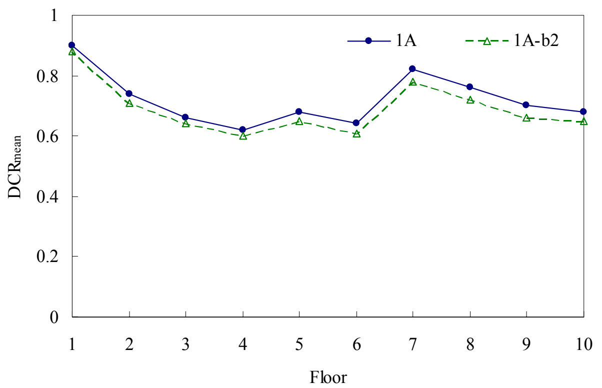

Fig. 4(c) Mean DCRs for Case 1A

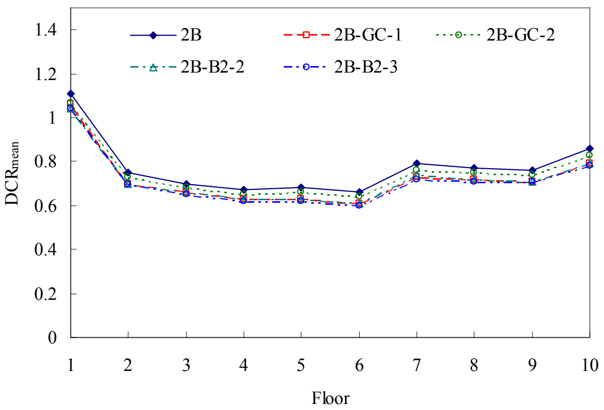

Fig. 4(d) Mean DCRs for Case 2B

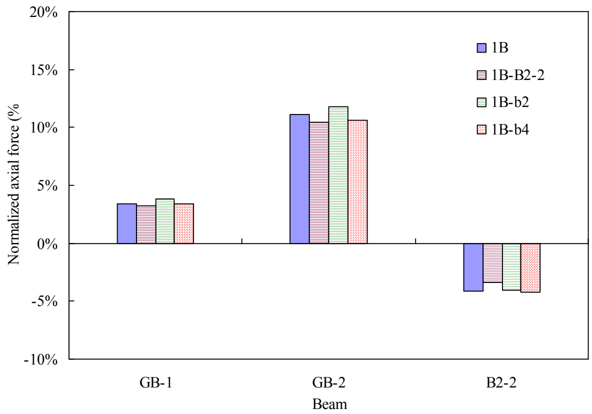

Fig. 5(a) Axial force of beams connected with the Case 1B column-removed point

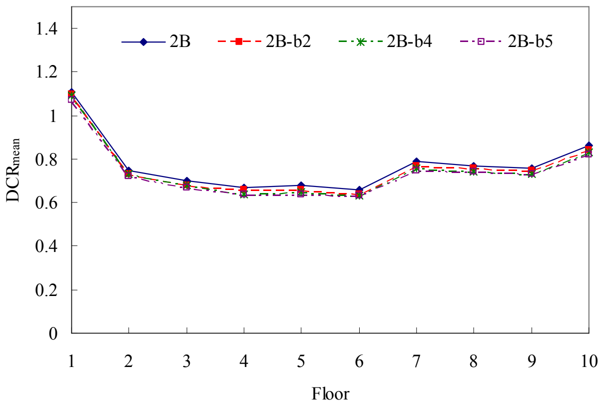

Fig. 4(e) Mean DCRs for Case 2B (continued)

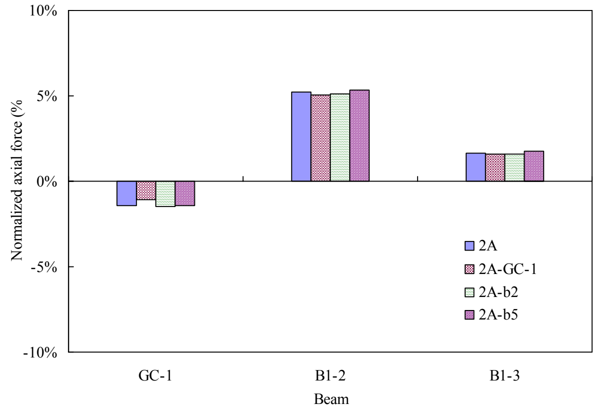

Fig. 5(b) Axial force of beams connected with the Case 2A column-removed point

When the first-story column is removed, the structural downward deformation may generate axial tension in the beams connected to the column-removed point. Figs.5(a)~5(e) present the normalized axial force of those beams under the four column-removed conditions with or without brick infill. Tensile axial force is normalized by the nominal tension strength of the beam member. Compressive force is normalized by the axial compressive strength obtained from the interaction diagram for combined bending and axial loads. It is observed from the figures that, for a peripheral or interior column loss condition, the two-span beam bridging the removed column may suffer from axial tension, as shown in Figs. 5(a), 5(b), 5(d) and 5(e). Axial compression is induced in the single span beam orthogonal to the two-span beam. Generally speaking, the brick-infill panel has minor effect on the axial force of those beams, except for Case 2B as shown in Fig.5(d). It is realized that for the interior column-loss condition of a planar frame, the brick-infill panels filled in the structural bay adjacent to the removed column may significantly increase the axial tension of the two-span beam. This may induce additional demand on the bonding of main reinforcement in the two-span beam.

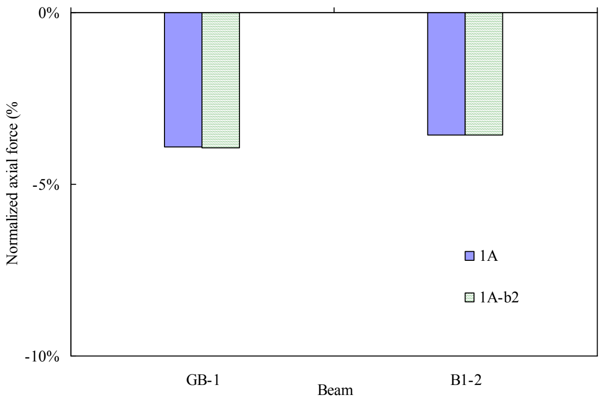

Fig. 5(c) Axial force of beams connected with the Case 1A column-removed point

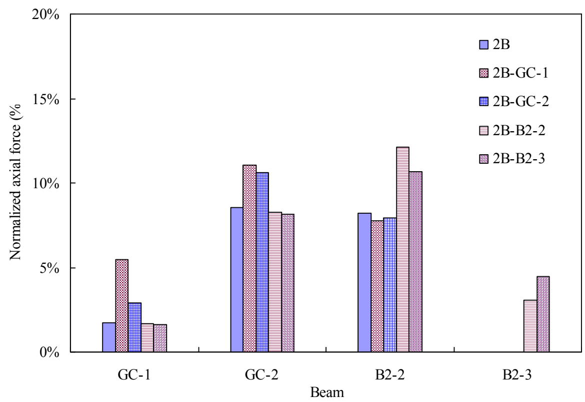

Fig. 5(d) Axial force of beams connected with the Case 2B column-removed point

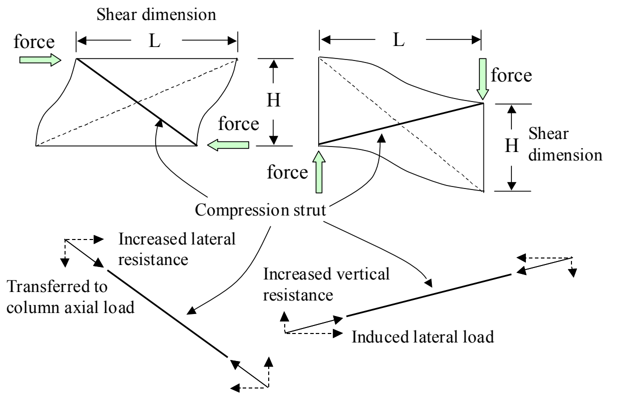

Fig. 6 Role of the compression strut under horizontal or vertical loadings

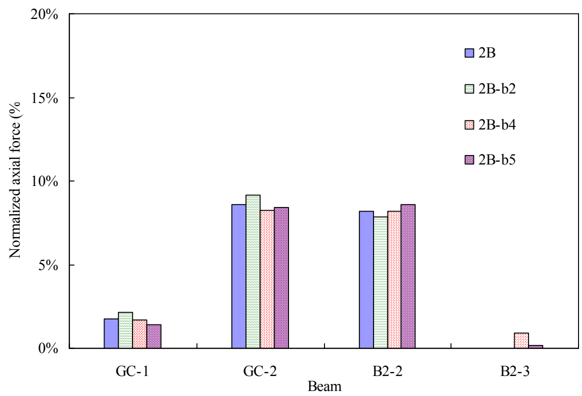

Fig. 5(e) Axial force of beams connected with the Case 2B column-removed point (continued)

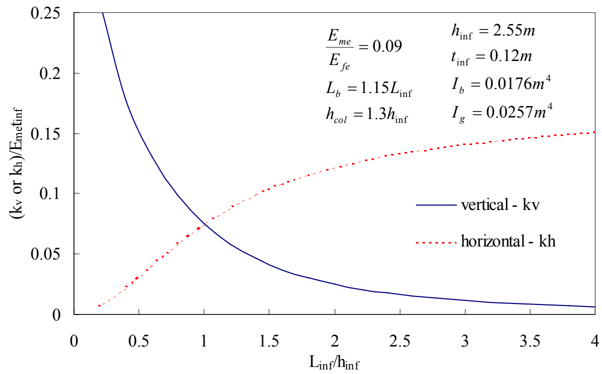

Fig. 7 Effect of the length-to-height ratio on the vertical and horizontal stiffness components

V. Discussion on the Effect

From the previous investigation, it appears that the effect of the brick infill on reducing the moment demand at the beam end of a column-removed building is not as significant as that observed from seismic response analyses [10, 16-17]. A major reason may be that, under horizontal earthquake excitations, all the brick-infill panels with a consistent longitudinal direction on a same story may affect the seismic response in the direction. However, as the building is subjected to sudden column loss, only the brick-infill panels filled in the column-removed bay may influence the vertical loading response. Also, a brick-infill panel confined by its perimetric beams and columns usually has a length-to-height ratio larger than 1. Hence, the shear dimension of the brick-infill panel subjected to horizontal seismic force is usually larger than that subjected to vertical downward loading, as explained in Fig. 6. Therefore, the vertical stiffness component of the brick panel is less than its horizontal component. Fig. 7 demonstrates the effect of the length-to-height ratio on the vertical and horizontal stiffness components of a compression strut. It is seen that the vertical stiffness contribution is decreasingly small as compared to horizontal one as the length-to-height ratio is larger than 1.5.

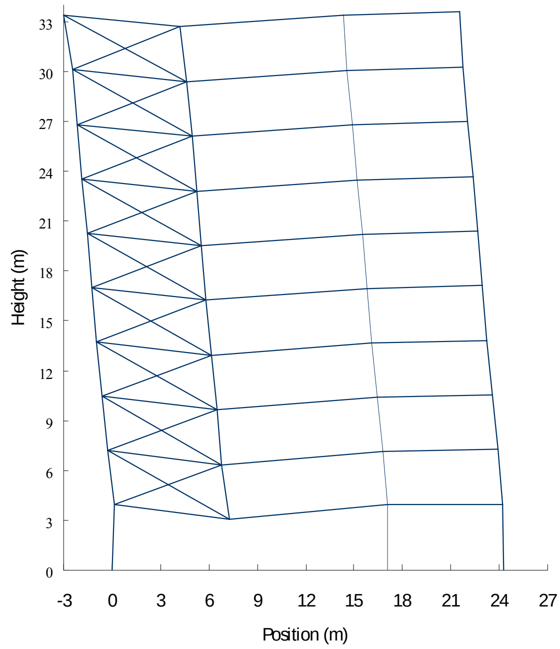

Fig. 8 Flexural deformation of the column lines

Moreover, from the investigation of a free-body diagram of the compression strut as shown in Fig. 6, the vertical force component of the strut under horizontal loadings is transferred as an axial load on the column, which usually has very high axial stiffness. However, the horizontal component of the strut under vertical loadings is a lateral load on the column. Thus, additional flexural deformation may be induced for the column, as shown in Fig. 8.

VI. Conclusions

The GSA linear static analysis method is used to evaluate the effect of interior brick-infill panels on the progressive collapse potential of an earthquake-resistant RC building subjected to sudden column loss. The analysis results indicate that the RC building has low progressive collapse potential. Compression strut elements are used to simulate the brick-infill panels. From the comparison of the demand-to-capacity ratio (DCR) of beam-end moment, it is realized that the DCR is generally reduced with consideration of the brick infill. Contribution of the brick infill to DCR reduction depends on its location and dimensions. More significant reduction is achieved as the brick-infill panels are filled in the structural bay adjacent to the removed column. Also, the shorter the span, the better the brick-infill contribution. For practical engineering, it may be reasonably conservative to consider the weight of brick-infill partitions only. However, an adverse effect on the two-span beam bridging the removed column is revealed. For the interior column-loss condition of a planar frame, the brick walls filled in the structural bay adjacent to the removed column may significantly increase the axial tension of the two-span beam.

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