

INFLUENCE OF INFILL WALL IN RC FRAMES

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Abstract. The function of infilled masonry reinforced concrete (RC) frame buildings during severe events such as blast caused by explosions or earth movement – earthquake and other significant lateral displacement could seriously damage a supporting frame column, causing the frame to collapse completely or partially. The behaviour of a framed structure associated with loss of supporting column as a result of vertical gravitational loading imbalance has received less attention in recent studies. When a supporting column is removed in a framed structure, it is assumed that the member deflection increases significantly, which could be restrained by the infill wall, resulting in contact forces between the infill wall and the frame. These interaction forces have an impact on the distributions of shear forces and bending moments along the frame components, which can contribute to frame stability or failure. The current study aims to address these key issues and gain insight into the performance of infilled-frame activity in the absence of a peripheral supporting column. This study's methodology is based on a numerical investigation of a typical RC infilled-frame subjected to gravitational loading using the three-dimensional discrete element code (3DEC) model. The scenarios considered include; investigation of the loaded structure with the column in place, without the column in place but supported by an infilled wall and with the effect of lateral load acting on the structure without a peripheral column support. The results indicate that masonry infill walls considerably increase the frame resistance to vertical load action, compared to the resistance of a bare frame up to 18%, therefore, the infill wall could play a major role in maintaining the structural system stability/integrity and reducing the likelihood of a progressive collapse.

Keywords: reinforced concrete frame, brick wall, progressive collapse, lateral constraint, peripheral column.

Introduction

The effect of infill walls on the progressive collapse behaviour of RC frames has recently got a lot of attention. As a result, a large number of numerical and experimental studies have been carried out to help us understand the effects of relevant parameters on the performance of RC sub-structures using high fidelity modeling with solid elements [1; 2] or global structures using macro-modeling with fibre elements, which has been refined using component-based joint models [3]. Around the world, residential and public structures have reinforced concrete frames with unreinforced masonry infill walls. In recent years, extreme stresses on buildings, such impact and blast, as well as other forms of destruction, like progressive collapse, have drawn increased attention. The latter could be the result of localized, severe damage to a supporting column for a reinforced concrete (RC) frame at the ground story level. A localized extreme column failure that affects the entire frame or a sizable portion of it and results in partial or complete collapse is what constitutes a support loss. One of the most striking instances of what a low probability-high consequence (LPHC) incident of this sort can result in terms of losses of life and property is the problem at hand [4-7].

One of the first instances of progressive collapse in the contemporary period was the 1968 fall of the Ronan Point residential tower in London as a result of a gas explosion. Additionally, the 2001 total collapse of the World Trade Centre in New York, US, and the 1995 bombing in Oklahoma City, which caused the Murrah Federal Building to partially collapse due to a truck bomb, showed how serious terrorist attacks can be on homeland security as well as how vulnerable a structure can be to abnormal loading if certain design criteria are not met. At the time, all design codes worldwide were intended to give a structure enough resistance, ductility, and redundancy to conventional actions like gravity loads, wind loads, earthquake-induced loads, and so on. However, after some of these deliberate building collapses, particularly in the United States [8-10], specific regulations to reduce the risk for progressive collapse in buildings were quickly released.

Mechanical and simulation properties

The models were analyzed using 3Dec software. In simulation with 3Dec, mortar joints are deleted from the model and their behaviour attributed to the discontinuities. 3Dec has predefined behaviour models for blocks (bricks) and discontinuities (mortar). Mohr-Coulomb plasticity model was used for bricks while for discontinuities the Coulomb slip model was employed. In the Coulomb model, elastic behaviour of discontinuities is introduced with normal stiffness ($N \cdot m^{-1}$) and shear stiffness ($N \cdot m^{-1}$).

Plastic behaviour of discontinuities is introduced with cohesion (Pa), friction angle (ϕ), dilation angle (ψ) and tensile strength (Pa). Material properties used for modeling with the distinct element method and 3Dec software are shown in Tables 1 and 2.

Table 1

Mechanical properties and other model inputs

Material	CL	Density, $\text{kg}\cdot\text{m}^{-3}$	Young Modulus, Pa	Poisson Ratio	Tensile Strength, Pa	Cohesion, Pa	Dilation Angle ψ	Friction angle ϕ
Foundation	Elastic	5000	8.00E + 10	0.23	-	-	-	-
RC Frame	Mohr Coulomb	2500	3.33E + 10	0.21	3.55E + 06	7.50E + 06	3.10E + 01	40
Brick	Mohr Coulomb	1875	3.33E + 10	0.15	1.60E + 06	2.30E + 06	3.10E + 01	45

Table 2

Modeling contact

Joint	Constitutive law	Normal Stiffness, $\text{N}\cdot\text{m}^{-1}$	Shear stiffness, $\text{N}\cdot\text{m}^{-1}$	Tensile strength, Pa	Cohesion, Pa	Dilation Angle ψ	Friction angle ϕ
RC Frame & Foundation	Elastic	5.70E + 11	1.70E + 10	-	-	-	-
RC frame & Brick	Coulomb	6.00E + 10	2.70E + 10	1.00E + 05	1.35E + 05	0.00E + 00	3.60E + 01

This present section discusses primary modeling techniques used in infilled frame simulation. The research presented in this paper was based on a numerical study that includes a static push-down analysis on a typical infilled structure subjected to gravitational loading transferred from the upper part of the building upon the removal of one supporting column. The elastoplastic constitutive law (Mohr-Coulomb) was adopted to study the mechanics of structural elements and infilled bricks. For mortar joints, the Coulomb constitutive law was used, which allows the tracking of mechanics of joints using the tangential and normal force. Both constitutive laws are existing models in the distinct element numerical software. A student free version of 3DEC software has been used, this aroused limitation in the type of mesh that could be employed. Due to this limitation, only six large infilled bricks could be modeled. The mortar-joint thickness was also embedded in that of the infilled bricks, and a coarse mesh was chosen for the whole structure.

Model development

In this section numerical analysis simulating a peripheral column removal scenario is carried out on two one-third scaled, 2-storey, 3-bay, planar bare and infilled frames as shown in Fig. 1.

The frames are made with detailing typical of Chinese structures of this kind and are intended to be nominally identical. The first floor interstorey height is 1.38 meters, while the other floors' interstorey heights are 1.30 meters. The center-to-center column spacing is 1.70 meters. All beams have a cross section of 150 x 100 mm² (height by width), and 4 x 8 longitudinal rebar is evenly distributed along their length. Stirrups with two legs and four legs each, spaced 30 mm apart, served as the transverse reinforcement. All columns are constructed with 12 x 8 longitudinal bars and a cross section of 200 x 200 mm², and 4-leg x 4-stirrups are available for transverse reinforcement. They are separated by 50 mm overall and by around 34 mm at the base of the ground floor columns.

The projected load demand under the column-removal scenario is compared with the bearing capacity, highlighting the most important affecting factors and calculating the capacity/demand ratios using an active method.

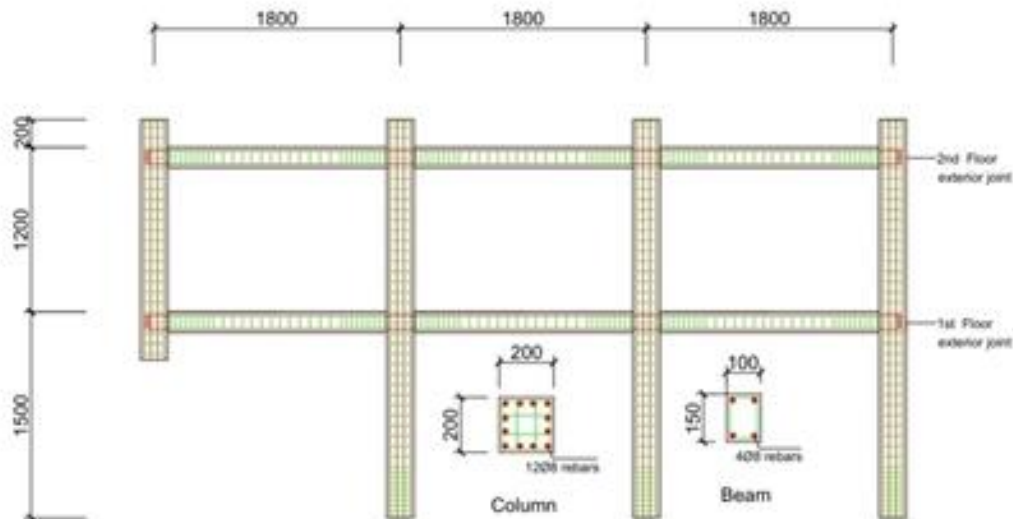


Fig. 1. RC frame with removed peripheral column

Structure presentation after removal of supporting column

Fig. 2 shows that the rigid block is used for both foundation and lateral constraint. The lateral constraint was positioned on the right side of the structure, away from the column to maintain the point of interest which is to be removed. All other elements (bricks, RC frame, joint) were defined as deformable elements to allow stress monitoring around the elements. Mesh size is limited to 100000 zones in the free version of 3DEC, therefore only a limited number of bricks could be simulated. To account for that, a general masonry wall was assumed by increasing the size of bricks which resulted to entire top part of the structure. The mesh size is chosen 111 division of each element in each axis by 2, making a total of 98943 zones. The results are described by the force-displacement relationship, that is, the variation of the vertical applied load with the vertical displacement of the loaded. Following, this information will be presented and discussed.

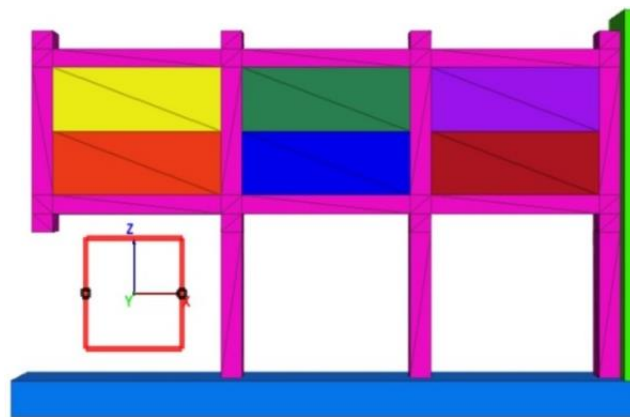


Fig. 2. Infilled frame after removal of supporting column

Results and discussion

In the following sub-sections, results of the different tests – load displacement and time frequency curves are presented. This involves the before and after case scenarios considered in this research.

Effect of column removal

For the before (do-nothing) and column removal scenario, this entails investigating the behaviour of the structure in its original state with all member/components intact and when the targeted external column was removed. The displacement with normalized time frequency of the system for the x-displacement and z-displacement is as presented in Fig. 3 and 4 respectively.

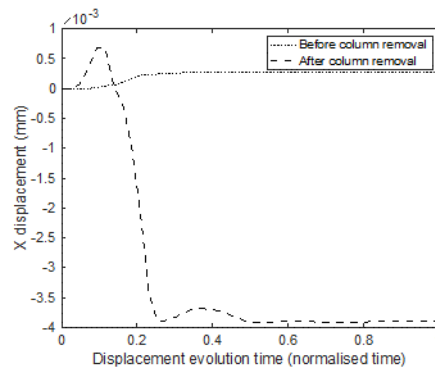


Fig. 3. X-displacement of structure before column removal

Fig. 3 reveals that, when the columns were intact under the influence of axial load only, there was low vertical displacement as shown by the relatively straight horizontal line, this was attributed to the sufficient resistance offered by the structure to oppose its self-weight before stabilization at equilibrium. This implies that there was no significant lateral displacements before the column removal. On the other hand, when one external column was removed, the structure experienced an initial server shock in the horizontal displacements as shown by the sharp decline (steep slope) in the curve before attaining partial equilibrium, there was significant displacement in the x-direction, the structure records 80% increase in vertical displacement about 3 times more. This was attributed to structural instability caused by the load imbalance that disturbed the structural equilibrium.

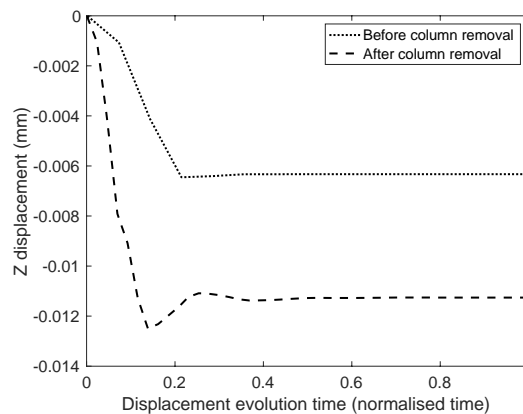


Fig. 4. Z-displacement of structure before column removal

Fig. 4 reveals that, the structure experienced relatively higher level of shock at its initial instance of load application before attaining stability possibly after the yield point. The displacement noticed for the before column removal scenario is relatively less compared to the after-column removal scenario. This was attributed to the self-weight effects or load and the structural instability conditions affecting the structure stability respectively.

Effects of brick wall

Though it has always been considered that the masonry elements of a structure do not take any part in the structure load resistance, however, it has also been argued that under extreme conditions, the masonry wall can take part in preventing a total collapse of the structure. To explore this phenomenon, in the current work, the column at the targeted spot was replaced with an infilled brick wall, then investigated for the before and after scenarios.

Fig. 5 presents the displacement versus time of infilled and bare frame behaviour on the X-direction. Fig. 5 reveals that the X-displacement tends to increase steadily in the negative direction from 0 mm with a relatively slow speed to 0.068 mm when without the brick wall, this was resisted by the structural impact caused by the initial strength – compressive stage. On the other hand, with the brick scenario also followed a similar pattern but with a relatively higher compressive strength which prevented further

displacement beyond 0.05 mm at increased displacement evolution time of 0.22, then the displacement remained constant until the end of the experiment. To explore further the trend, it was imperative to look into the stress revolution of the two set ups as shown in Figure 6. The higher compressive stresses to the structure with the brick wall are attributed to the increased weight of the masonry part, it is interesting that the structure with the brick wall recorded less and stable shear stresses compared to when the brick walls were absent. This is another evidence to suggest that the presence of the masonry part (brick wall) increases the bearing capacity of the structure.

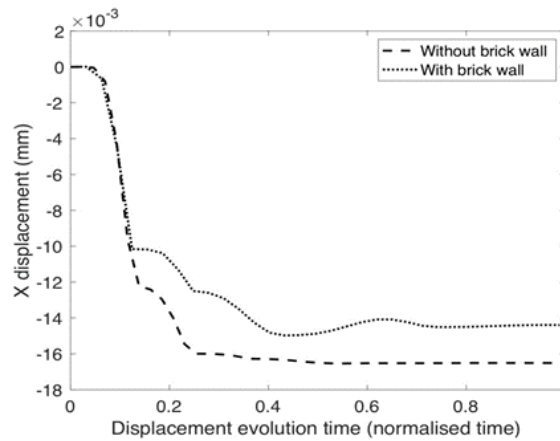


Fig. 5. Displacement versus time of infilled and bare frame on X-direction

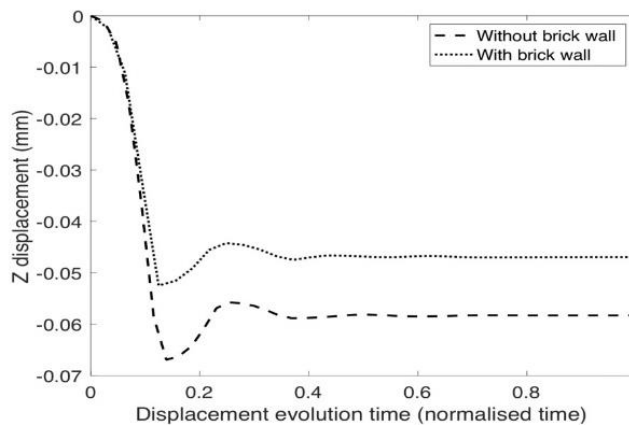


Fig. 6. Displacement versus time of infilled and bare frame on Z-direction

Fig. 7 and 8 also show the behavior of compressive shear and stresses against stress evolution time for the framed structure respectively.

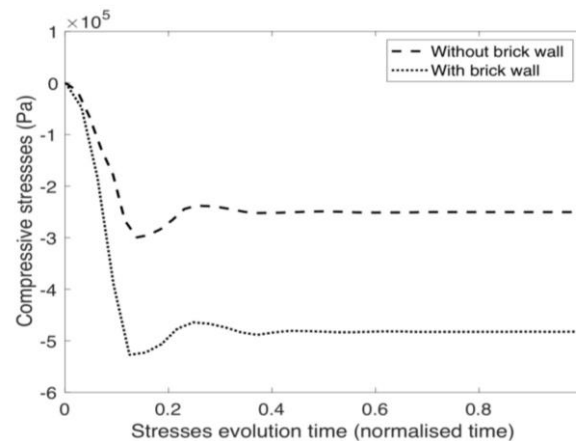


Fig. 7. Compressive stresses versus stress evolution time of the frame

Fig.7 and 8 revealed that, there was a sharp stress effect on the framed structure at the beginning of the experiment – initial stage of applied load, but the structure adjusted its equilibrium based on strength to withstand the applied load, hence the sharp decline in the curve at the initial stage which rose up steadily to attain a stably state till the end on the experiment for both without and with infill wall scenarios.

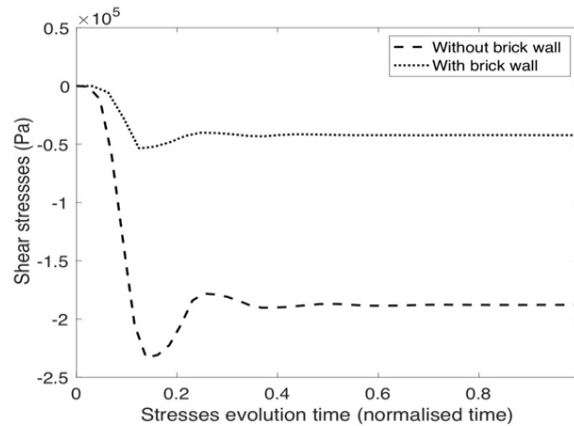


Fig. 8. Shear stresses versus stress evolution time of the frame

Conclusions

The progressive collapse processes of the specimens that revealed the bending capacities of the beams with associated resistance forces based on the loading stages (scenarios) are evaluated in this study. In each case, the infill walls contributed to the resisting force and acted as compressive struts. The simulated model showed that the strained regions first moved horizontally outward before turning inward, and that when the removed column's vertical displacement rose, the displacements of the regions at the second storey gradually surpassed those at the first story. Infill walls altered the distribution of rebar strain in the beams but had no effect on the distribution of rebar strain in the columns. As the maximum resistance force of the infilled frame was 1.57 times that of the bare frame, the infilled frame had a larger outward horizontal displacement of regions, and the vertical displacements of the removed column corresponding to the maximum outward horizontal displacement of regions of the two specimens were -1.11×10^{-5} mm and -1.11×10^5 mm, respectively. As a result, the presence of infill walls changed the load transfer path and failure mode of the frames. For the bare frame and the infilled frame, the catenary stage began at vertical displacements of 204.5 mm and 215.5 mm, respectively. It could therefore be concluded that the infill walls reduced the ductility performance of the frame.

Author contributions

All the authors have contributed equally to creation of this article.

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