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Utilizing Steel Brace for Seismic Retrofitting of Old School Buildings with Open Ground Storey

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ABSTRACT: This paper investigates the seismic performance of an old school building with open ground storey. The building was designed according to an old Egyptian design code that did not consider the earthquake load; thus, the building is vulnerable to sudden lack of stiffness in the open ground storey (soft storey effect). The first check showed that the building is unable to resist the loads from earthquakes in both longitudinal and transverse directions. Therefore, two retrofitting options were suggested and investigated: using steel bracings; and changing the thickness of some ground floor infill walls. Pushover analyses were conducted to evaluate the building seismic performance. For these analyses, the FEA was applied considering both material and geometric nonlinearities. Both retrofitting methods helped to make the building capable to resist the earthquake loads according to the current Egyptian codes. In particular, retrofitting increased the lateral resistance by up to 55% and 25% in longitudinal and transverse directions, respectively. The research findings facilitate an economical and practical upgrading of many old school buildings without violating their function. Based on authors' experience, there are hundreds of such school buildings in Egypt alone.

Keywords: Reinforced Concrete School, Soft Storey, Seismic Analysis, Retrofitting by Steel Bracing, Finite Element Analysis.

1 INTRODUCTION

Unfortunately, most old buildings in Egypt that were constructed before the 1992 earthquake were designed and detailed to resist minimal or no earthquake loads, Sameh (2016) [1]. For example, the reinforcement details of stirrups at ends of columns and beams had no special seismic details which do not conform to recent design codes including the Egyptian code ECP-201, ACI (2014) [2]. Reinforced concrete structures with masonry infill walls were very common in Egypt at that era and even today. For old design codes, the effect of soft storey (a sudden reduction in stiffness in the storey) was not considered. Nevertheless, presence of a soft storey increases the inter-storey drift in that storey and may cause collapse of that storey leading to the collapse of the entire building, Guevara-Perez (2012) [3]. The impact of soft storey has been clearly addressed in modern codes. For example, the Eurocode [4] for earthquake resistant design of structures requires an increase in the resistance of the columns in the soft stories, by increasing their internal forces due to seismic actions in order to prevent formation of a plastic side sway story mechanism. The first failure in the buildings occurs in the infill walls in the ground storey because the larger drift occurs in the lower storey, Feng et al. (2014) [5]. The building can be strengthened at the open ground floor only by steel brace that effectively improves overall behaviour of the building under the earthquake loads by removing the soft storey weakness, Antonopoulos and Anagnostopoulos (2012) [6]. That will allow the building to remain operational during the retrofitting with no increase of the building weight and with relatively cost effective with an easy way of application, Antonopoulos and Anagnostopoulos (2013) [7]. Steel brace have multiple shapes, like chevron bracing and knee bracing, that fit architecturally so that the freedom of movement does not impede in the ground floor and it is proved that they were able to increase the stiffness and strength of the structures, Huang et al. (2015) and Leelataviwat et al. (2017) [8, 9]. Pushover analyses is used for assessment and retrofitting process of the buildings. The pushover analysis helps in understanding the deformation and cracking of a structure in case of earthquake. It gives a kind of fair understanding of the deformation of building and formation of plastic hinges in the structure, Krawinker and Seneviratna (1998), [10] and it is considered as an approximate tool to understand the building performance. The building will be evaluated before and after the retrofitting by Egyptian code at which the school building is located in the third zone, with a ground acceleration of 0.15g and the soil classified as type C, ECP-201 (2012) [11]. The cross sectional dimensions and the grade of steel brace that will be used for retrofitting in the ground storey are designed according to Egyptian Code ECP-205 (2012) [12]. The main objective of this paper is to examine whether a good and cheap retrofitting solution can be found for strengthening the buildings with steel brace in the open ground storey only which will help retrofitting hundreds of school buildings in Egypt and can be expanded to other buildings that have the same situation.

2 BUILDING DESCRIPTION

The school consists of a ground storey and three typical top storeys. Ground storey height is 4 meters while the upper storeys are 3.5 meters high, each. The school building is consisted of three parts as shown in Figure 1.

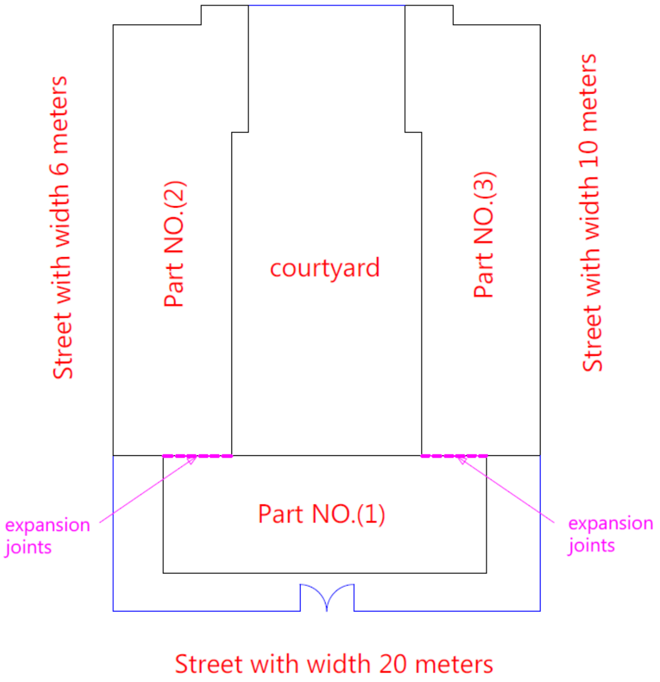


Figure 1. The three parts of school building.

The three parts are isolated from each other by expansion joints. All the masonry infill walls in the building are 12 cm thick. Part No. (1) will be evaluated only because it has a free space (soft storey) in the ground storey, which reduces its ability to resist earthquakes more than other buildings, as shown in Figures 2 and 3. The building will be referred to part NO. (1). Locations and distances between columns and beams are shown in Figure 4. The details of columns and beams at section (S-S) are shown in Figure 5. The details of columns and beams are listed in Tables 1 and 2, respectively.

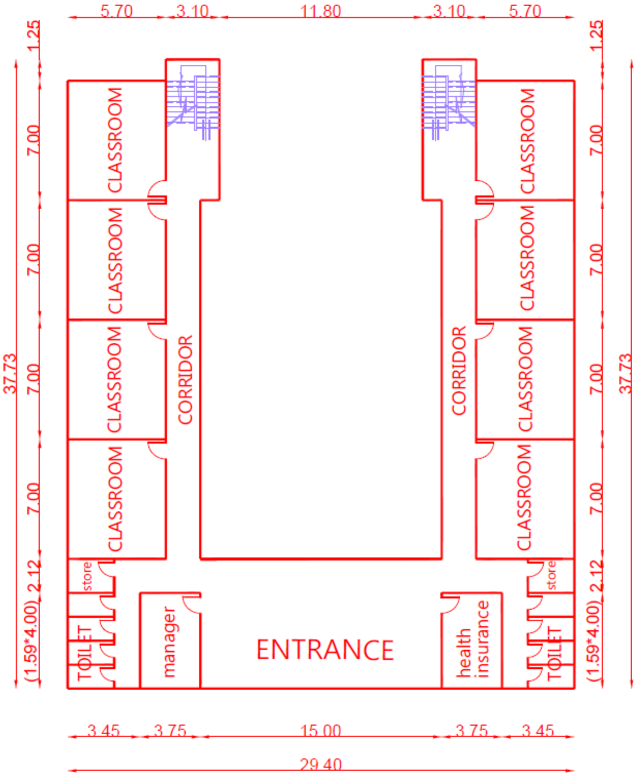


Figure 2. Ground floor architectural plan.

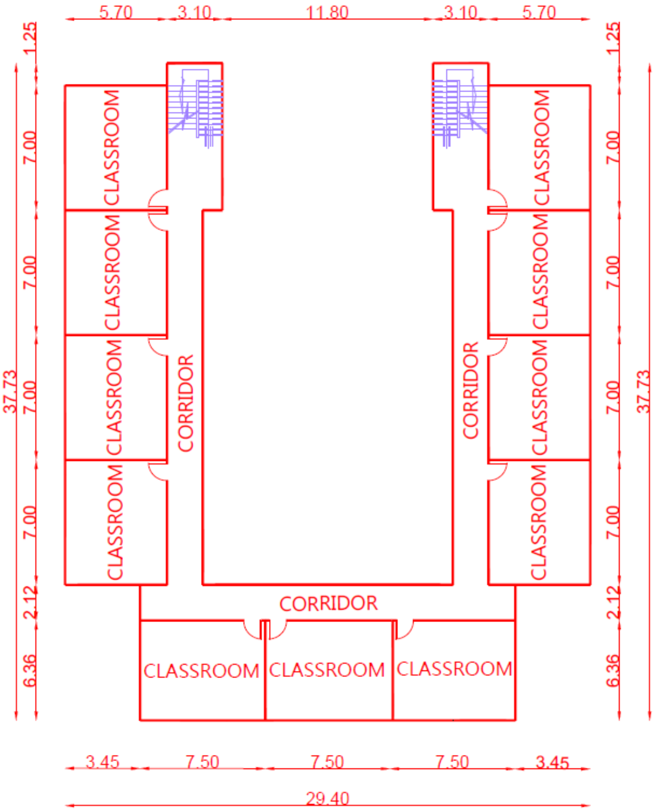


Figure 3. Typical floor architectural plan.

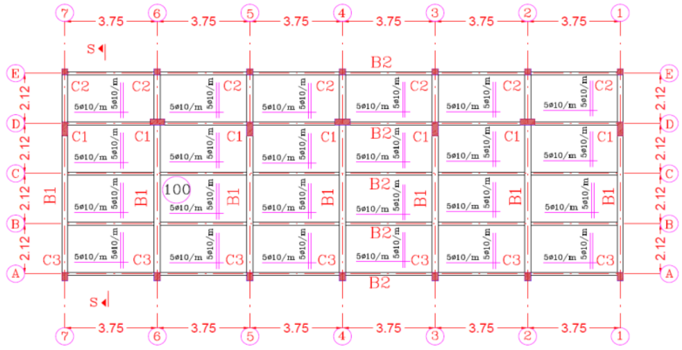


Figure 4. Structural details for ground and typical floor for part NO. (1).

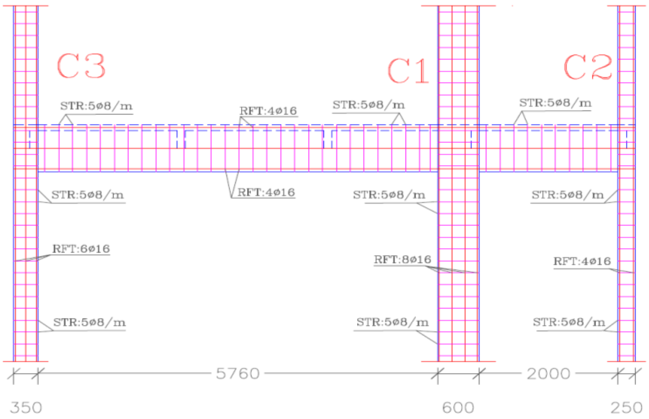


Figure 5. Details of columns and beam at section (S-S).

Table 1. Details of building columns.

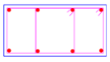
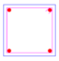
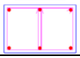
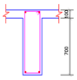
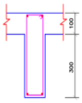
Col.	Dimensions (mm)	(RFT)	Stirrups (STR)	Cross sections Shape
C1	250×600	8ϕ16	5ϕ8/m	
C2	250×250	4ϕ16	5ϕ8/m	
C3	250×350	6ϕ16	5ϕ8/m	

Table 2. Details of buildings' beams.

Beam	Cross section (mm)	Top (RFT)	Bottom (RFT)	Stirrups (STR)	Cross sections Shape
B1	250×800	4ϕ16	4ϕ16	5ϕ8/m	
B2	120×400	2ϕ12	2ϕ12	5ϕ8/m	

3 INITE ELEMENT MODELING

A three-dimensional finite element model of the building was modelled using the ANSYS software as shown in Figure 6. The previously mentioned concrete dimensions for all structural elements were taken into consideration with the existing elements reinforcements.

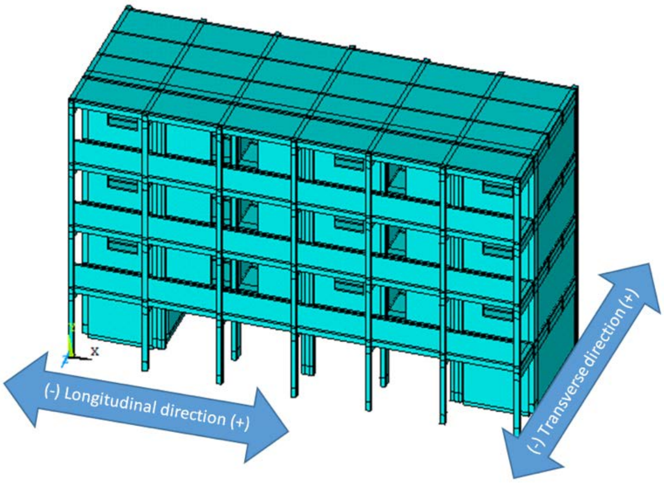


Figure 6. Three-dimensional model of the school building.

3.1 *Element Types*

Concrete and infill walls were modelled using SOLID65 element as the element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. The cracking of concrete controls the failure of the model. It is assumed that the concrete is a homogeneous and initially isotropic. Fanning (2001) [13] used the discrete and smeared model for reinforced concrete and it was found that the discrete model for reinforcement is the best for the analysis. By using the discrete model for reinforcement, the concrete and the reinforcement mesh share the same nodes and concrete occupies the same regions occupied by the reinforcement. Steel bracing was modelled by SOLID185 element because the element has plasticity, stress stiffening, large deflection, and large strain capabilities and it is appropriate for homogeneous material. CONTA174 and TARGE170 elements were used as a pair to represent the interface between the infill walls and reinforced concretes, Mohyeddin et al. (2013) and Alva et al. (2015) [19, 20]. The behavior of contact surface is standard (allows sliding and separation). A value of μ = 0.5 was considered for the coefficient of friction between the reinforced concrete and the infill wall.

3.2 *Material Properties*

The compressive uniaxial stress-strain relationship for the concrete model was obtained using the following equations to compute the multilinear isotropic stress-strain curve, MacGregor (1992) [14]. The multilinear isotropic material uses the Von-Mises failure criterion along with the Willam and Warnke (1975) [15] model to define the failure of the concrete. The equations that were used to compute stress-strain curve shown in Figure 7 are:

$$\mathrm{f} = \frac{E_c \varepsilon}{1 + \left(\frac{\varepsilon}{\varepsilon_0}\right)^2} \qquad (1)$$

$$\varepsilon_0 = \frac{2\mathrm{f}`_c}{E_c} \qquad (2)$$

$$E_c = \frac{\mathrm{f}}{\varepsilon} \qquad (3)$$

where

f = stress at any strain

ε = strain at stress f

ε_0 = strain at ultimate compressive strength.

E_c = concrete modulus of Elasticity.

$\mathrm{f}`_c$ = uniaxial cracking stress.

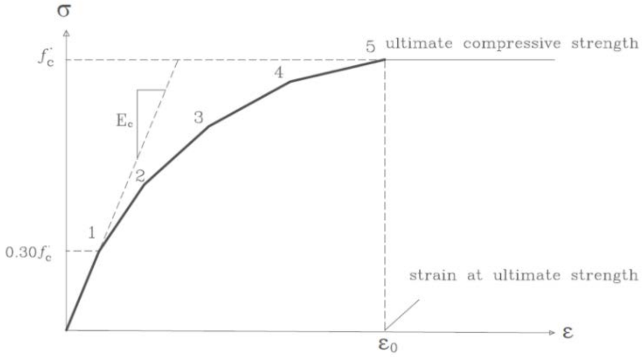


Figure 7. Simplified compressive uniaxial stress-strain curve for concrete.

The first point is assumed as for calculating the linear part 0.3f`c and the rest of the curve is nonlinear. The properties of concrete and infill walls that were considered in the finite element analysis are listed in Table 3.

Table 3. Properties of concrete and infill walls.

Material	ρ (kN/m³)	$\mathrm{f}`_c$ (MPa)	f_{ctr} (MPa)	E_c (MPa)	ν
Concrete	24	16	2.8	18824	0.2
Infill walls	18	4	1.4	9375	0.2

The stress–strain relationship for steel is modelled with a bilinear representation, identical in tension and compression, as shown in Figure 8. The properties of reinforcement steel and steel bracing considered in the finite element analysis are listed in Table 4.

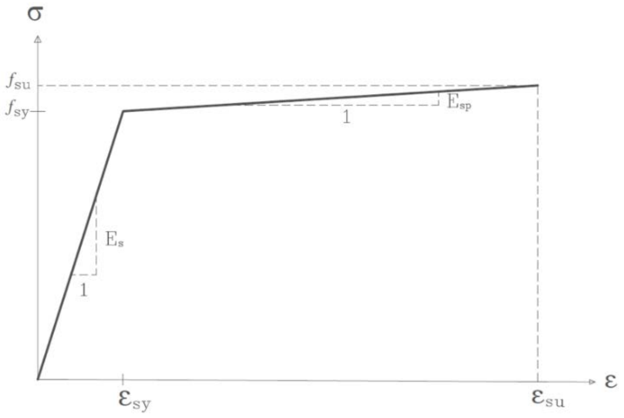


Figure 8. Idealization of steel stress–strain behaviour.

Table 4. Properties of steel reinforcement and steel bracing

Material	ρ (kN/m³)	ν	E_s (GPa)	f_{sy} (MPa)	Tangent E_{sp}
Steel bars	78.5	0.3	200	240	2.5% of E_s
Steel Bracing	78.5	0.3	200	360	2.5% of E_s

4 ASSESMENT IN TRANSVERSE DIRCTION

It was observed that the evaluation of the building transverse response varied when the direction of load changed because the infill walls that include door in ground storey are not symmetric (the door location made them asymmetrical), as shown in Figure 9. The infill wall with door has more initial lateral stiffness when loads act in positive direction than when loads act in negative direction.

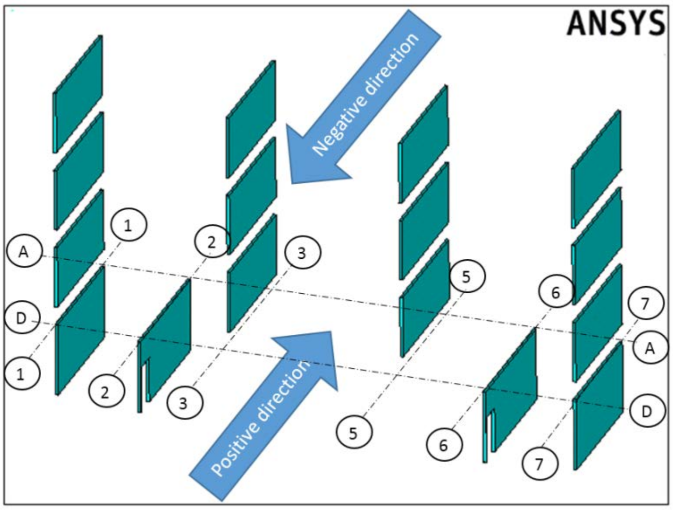


Figure 9. Configuration of infill walls in transverse direction.

It was observed that the different locations of door openings in the infill walls change the lateral stiffness, Hammoudah et al. (2017) [16]. The door located near to vertical edge decreases the effectiveness of infill wall to resist the lateral loads as it lies in the path of stresses. While for the other load direction, the door is not in the path of the stresses so the effectiveness of the wall is higher. In the negative transverse direction, the base shear equals 68 ton and the ground acceleration is 0.135g (not safe for this building). The corresponding building drift is shown in Figure 10. In the positive transverse direction, the base shear equals 80 ton and the ground acceleration is 0.159g (safe for this building). The corresponding building drift is shown in Figure 11.

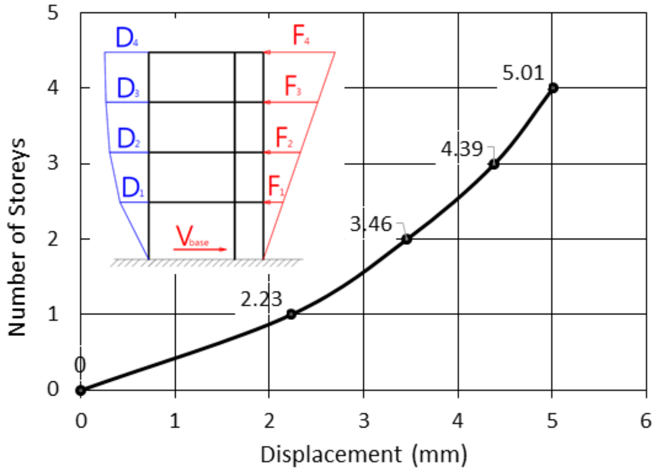


Figure 10. Building drift in the negative Z-direction at failure (V=68 ton).

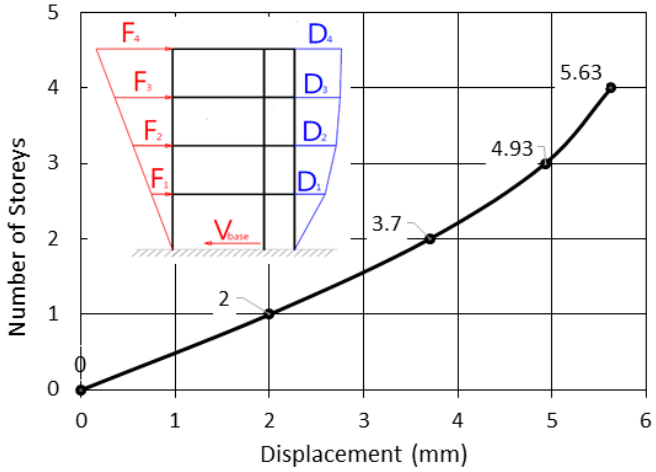


Figure 11. Building drift in the positive Z-direction at failure (V=80 ton).

It was observed from building drift in the negative transverse direction that the drift in the ground storey represents 44 % of the total drift of the building. That was a result of the lack of infill walls in the ground storey compared to the upper storeys and also in this direction, the infill walls with door are not efficient. It was observed from building drift in the positive transverse direction that the drift in the ground storey represents 35 % of the total drift of the building that is less than the negative direction because at this direction the door was not in the path of the stresses and so the infill walls with door are more efficient.

The effect of the door location relative to the path of stresses is as shown in Figures 12 and 13 and the failure in both cases occurred in the infill walls located at the ground floor.

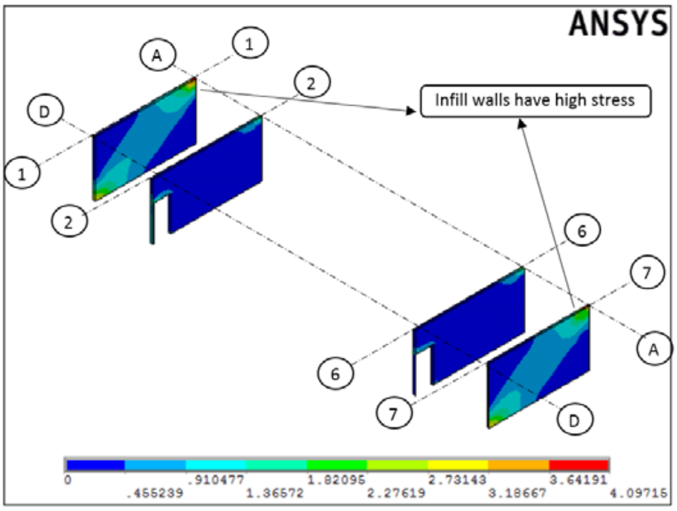


Figure 12. Door in the path of stresses when loads act in negative transverse Z-direction.

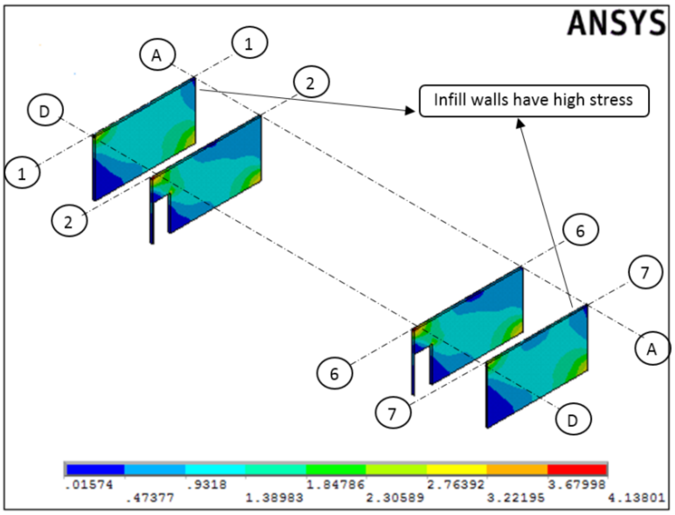


Figure 13. Door is not in the path of stresses when loads act in positive transverse Z-direction.

4.1 *Retrofitting in Transverse Direction*

The cheapest and easiest way to strengthen the current building is to replace the infill walls with doors next to column at axis (2-2) & (6-6), 12 cm-thick, by infill walls with a thickness of 25 cm and with the door located in the middle of the wall, as shown in Figure 14. With this change, failure occurred first at the infill wall in the ground storey as shown in Figure 15. For loads acting in either negative or positive transverse direction, the resultant base shear is 98 ton and the ground acceleration is 0.194g (safe for this building) and the final inter-storey drift is as shown in Figure 16.

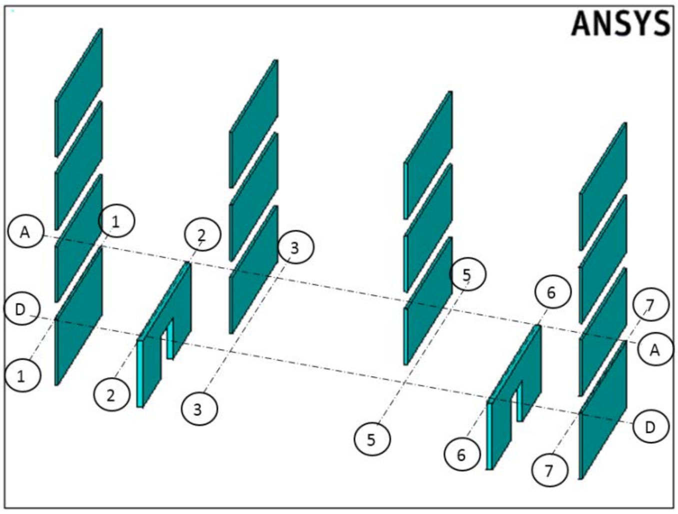


Figure 14. Configuration of infill wall after modification.

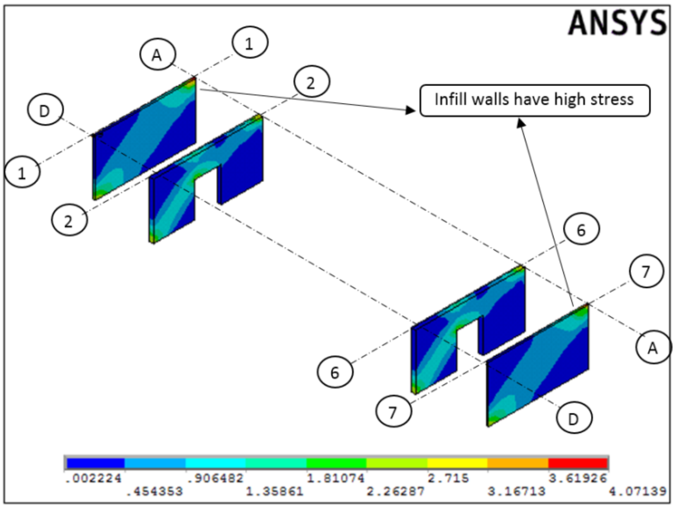


Figure 15. Stresses in infill walls at the failure after modification in infill walls at ground storey in transverse Z-direction.

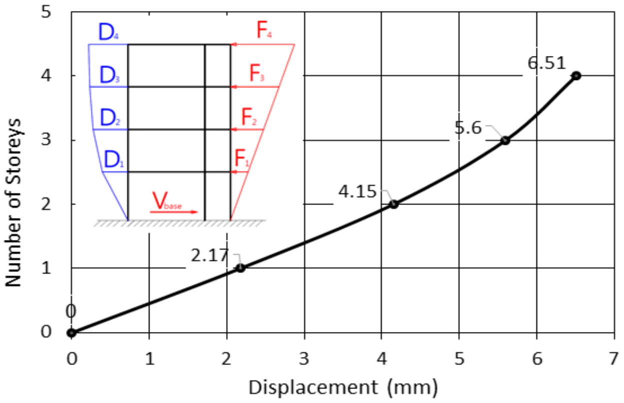


Figure 16. Building drift in transverse Z-direction after modification in infill walls at ground storey at failure (V=98 ton).

It can be seen from building drift in this retrofit that the drift in the ground storey represents 33 % of the total drift of the building. Thus, the soft storey effect is decreased. Besides, the base shear increased by about 44%. Relocating the door in the middle of infill wall increased the lateral stiffness in negative and positive directions. The double thick wall gives almost twice the stiffness and strength of a single thick (12 cm) wall.

4.2 *Assessment in Transverse Direction (Open Ground Storey)*

As an architecture requirement for the existing school, it was decided to remove inner wall from the ground storey. Therefore, the manager room as well as the health insurance room, Figure 2, will be included into the whole school entrance. However, there is no need to remove the infill walls at axis (1-1) & (7-7), as shown in Figure 17.

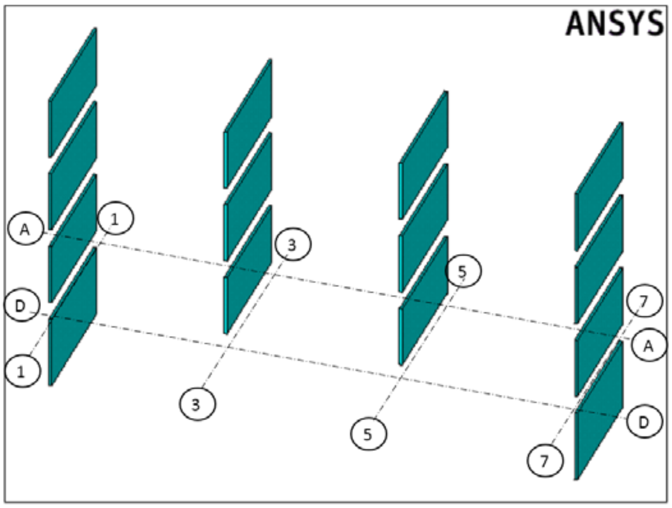


Figure 17. The configuration of infill wall in transverse Z-direction after removing inner walls from ground storey.

For this load case, the base shear is 65 ton and the ground acceleration is 0.129g (not safe for this building). The building drift is as shown in Figure 18. It is observed from building drift after removing inner infill walls from ground storey that the drift in the ground storey represents 46 % of the total drift of the building because of the lack of infill walls in the ground storey compared to the upper typical storeys so the failure occurred in the infill walls in the ground storey, as shown in Figure 19.

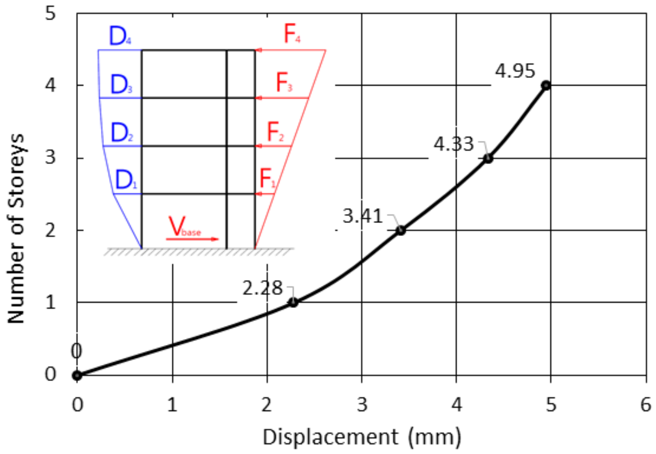


Figure 18. Building drift after removing inner walls from ground storey in transverse direction at failure (V=65 ton).

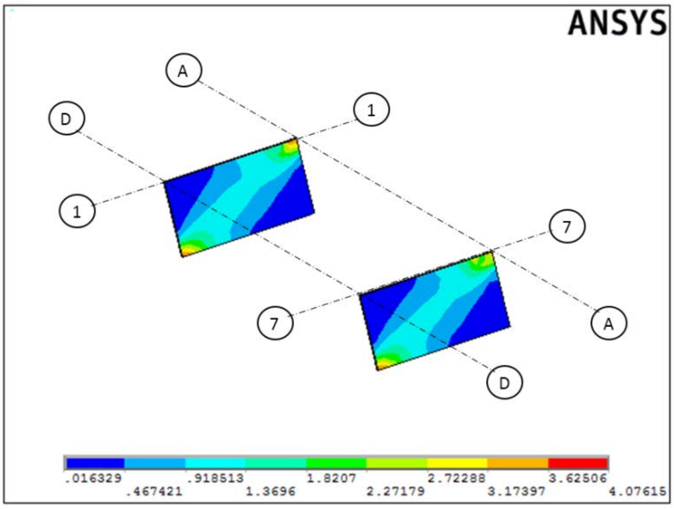


Figure 19. Stresses in infill wall at the failure after removing inner walls from ground storey.

4.3 *Retrofitting in Transverse Direction (Open Ground Storey)*

Steel bracing is much effective to be used for the retrofitting especially the knee bracing located at axis (4-4), as in Figure 20. The cross-sectional dimensions of knee bracing and the dimensions of steel plates used are listed in Tables 5 and 6, respectively. It was observed that the base shear is 85 ton and the ground acceleration is 0.168g (safe for this building). The building drift is shown in Figure 21. It was observed from the building drift after retrofitting using knee steel brace that the drift in the ground storey represents 49 % of the total drift of the building so the failure happened in infill walls located at the sides in the ground storey. It can be seen that the steel bracing gives more deformation in the ground storey than the infill walls but gives more load carrying capacity for the ground storey in general. The failure of the infill walls in the ground storey is shown in Figure 22.

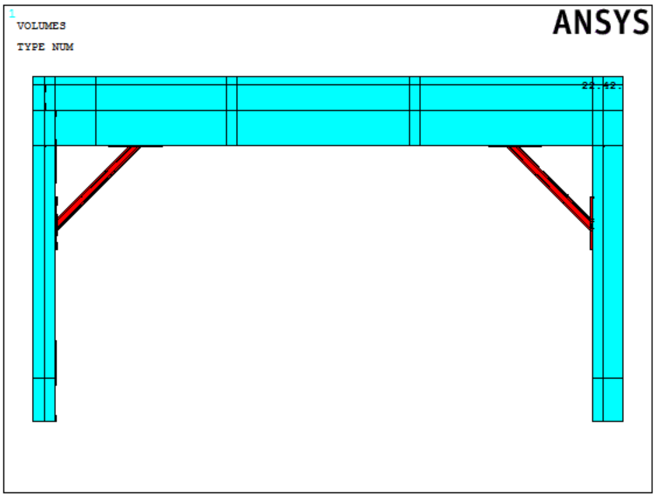


Figure 20. Knee bracing.

Table 5. The cross section dimensions of knee bracing.

Bracing type	Box –Section Dimensions (mm)	Cross section shape
Knee	200×100×20	

Table 6: The dimensions of plates at the ends of knee bracing.

Plate	Thickness (mm)	Length (mm)	Width (mm)
Upper Plate	20	600	250
Lower Plate	20	600	250

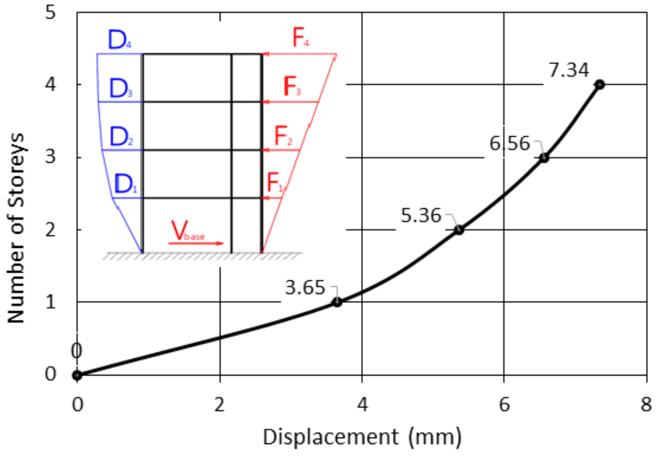


Figure 21. The building drift after retrofitted using knee steel brace at failure (V=85 ton).

Knee bracing was used because it is cheaper and gives a good architectural shape that allows the use of the ground space and also strengthens the building and makes it safe against the earthquake loads. When using eccentric bracing instead of the knee bracing in this condition, it is found that the load carrying capacity of the building did not differ greatly because the failure occurred in the infill walls located at the sides of the ground storey and therefore the use of the knee bracing is the cheapest and in both cases is successful.

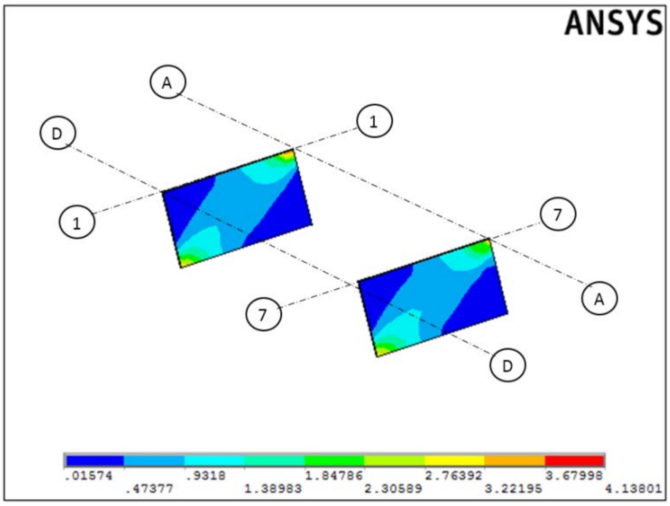


Figure 22. The place of failure in the infill walls in the ground storey after retrofitted using steel brace.

It was observed that the base shear for the building after retrofitting without the open ground floor suggestion (retrofit by modifying the infill walls in the ground storey) increased by about 44% compared to the base shear for the building without change. But, the base shear for the building after retrofitting by knee brace in the ground storey increased by about 31% compare to the building after removing inner walls in ground storey without retrofit. All base shear values of the building in transverse direction are shown in Figure 23.

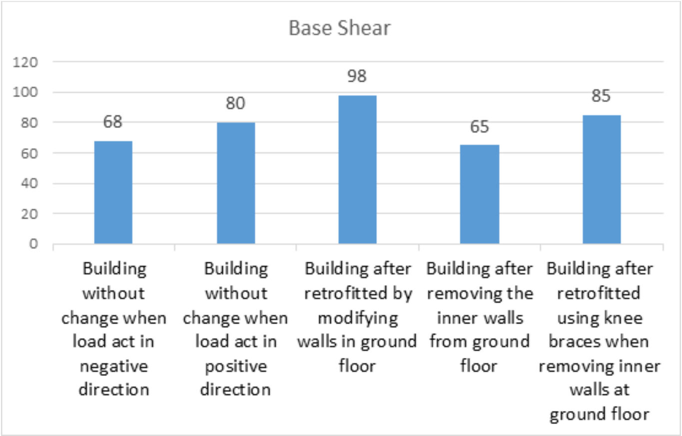


Figure 23. The base shear of the buildings in transverse direction.

5 ASSESMENT IN LONGITUDINAL DIRCTION

In this direction, there is sufficient symmetry in the infill walls in the ground storey which makes the evaluation nevertheless enough in one direction only, either positive or negative loading directions. The structure was evaluated in both positive and negative directions in the longitudinal direction and it is found that the difference is very small and cab be neglected. So, the solutions in one direction only will be presented. The building is first evaluated without any change in the infill walls. The infill wall configuration is shown in Figure 24.

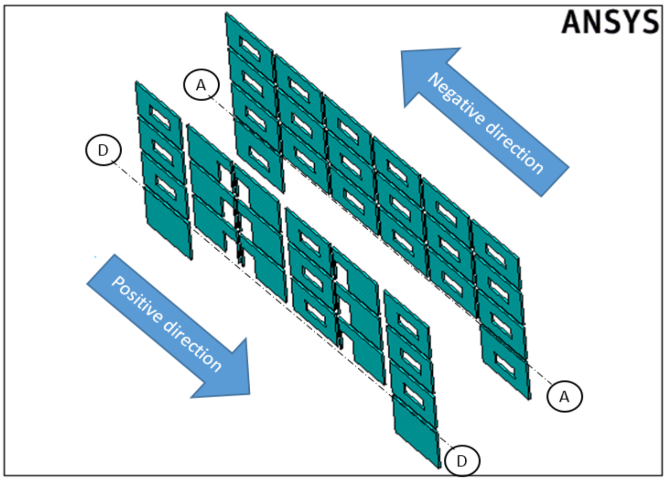


Figure 24. The infill walls configuration.

The base shear equals 62 ton and the ground acceleration is 0.123g (not safe for this building). The accompanied building drift is shown in Figure 25. It is observed from the inter-storey drift in this condition that the drift in the ground storey represents 63 % of the total drift of the building due to the lack of infill walls in the ground storey compared to the upper storeys. Thus, failure occurred in the infill walls located in the ground storey, as shown in Figure 26.

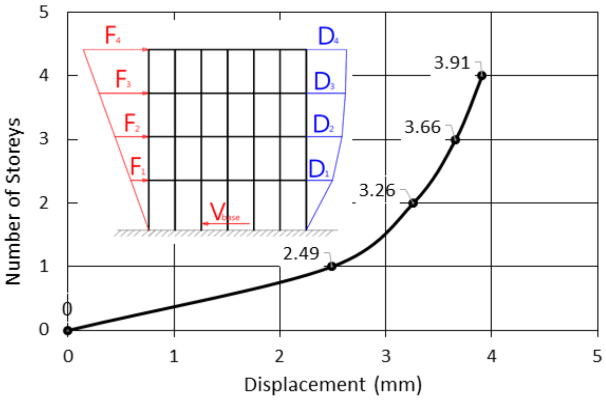


Figure 25. Building drift in longitudinal direction without any change at failure (V=62 ton).

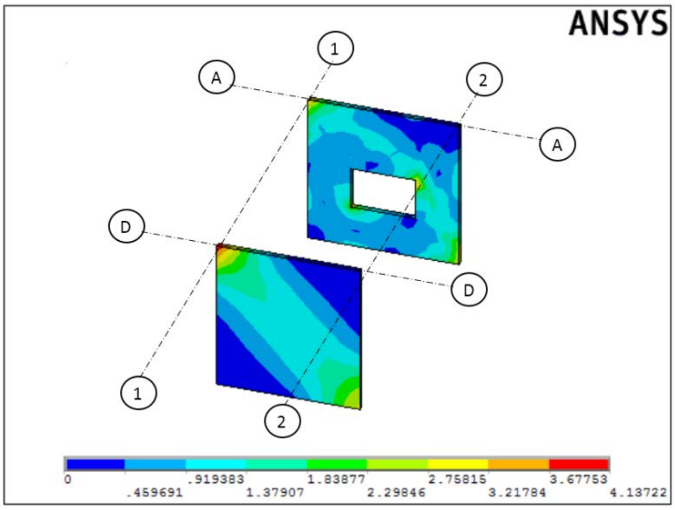


Figure 26. The infill walls' stresses at the failure.

5.1 *Assessment in Longitudinal Direction (Open Ground Storey)*

In the case when infill has to be removed from the ground floor, the base shear observed to be 46 ton and the ground acceleration is 0.091g (not safe for this building) and the accompanied building drift is as shown in Figure 27.

It is observed from the inter-storey drift in this condition that the drift in the ground floor represents 90 % of the total drift of the building because there are no infill walls in the ground storey. The collapse occurred first at the bottom of the column (C1) at axis (4-4) then at the bottom of the column (C1) at axes (2-2) and (6-6), as shown in Figure 28.

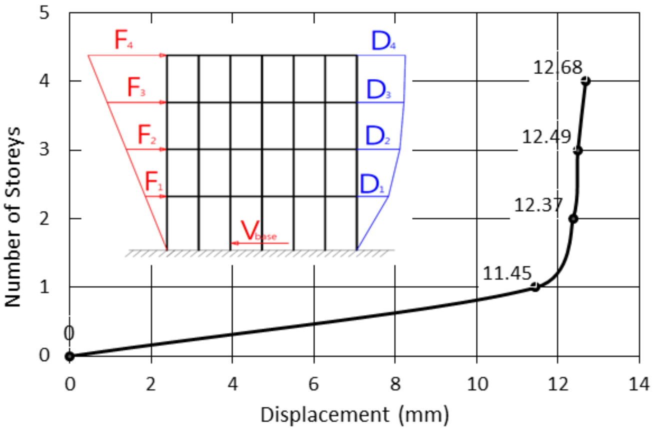


Figure 27. Building drift in longitudinal direction after removing inner walls from ground storey (V=46 ton).

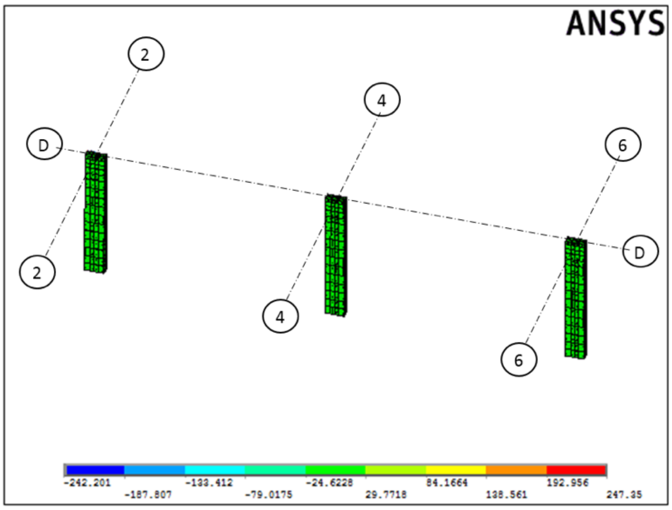


Figure 28. the failure in the columns.

5.2 *Retrofitting in Longitudinal Direction (Open Ground Storey)*

As a result of previous discussion, the building has to be strengthened in the longitudinal direction. A chevron braced is used in the ground floor to allow the movement with accepted architectural view, as shown in Figure 29.

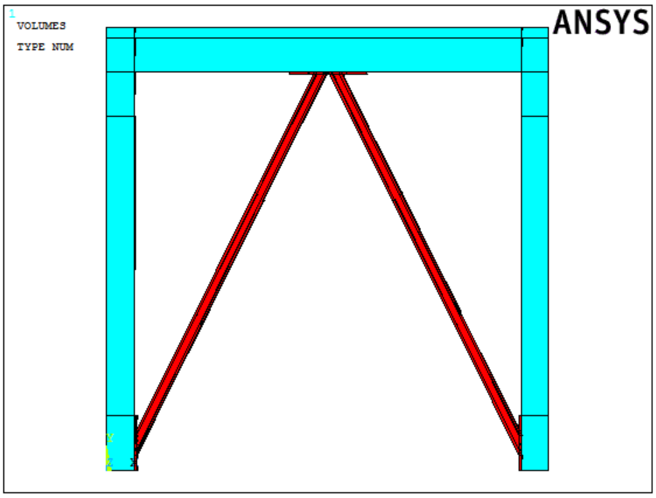


Figure 29. Chevron bracing.

The cross-section dimensions of chevron bracing and the dimensions of its plates are listed in Tables 7 and 8, respectively. Chevron braced was used at axes (A-A) and (E-E), between axes (1-1) and (2-2), and between axes (6-6) and (7-7).

Table 7. Cross-section dimensions of chevron bracing.

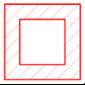
Bracing type	Box-Section dimensions (mm)	Cross section shape
Chevron	100×100×20	

Table 8. Dimensions of plates at the ends of chevron bracing.

Plate	Thickness (mm)	Length (mm)	Width (mm)
Upper Plate	20	700	120
Lower Plate	20	500	120

The base shear was 96 ton with ground acceleration of 0.19g (safe for this building) and the resultant building drift is shown in Figure 30. It is observed from the inter-storey drift in this retrofit that the drift in the ground storey represents 88 % of the total drift of the building and the failure occurred in infill walls in the first storey. Thus, the steel bracings didn't much reduce the drift in the ground storey but increased the load carrying capacity for the ground storey.

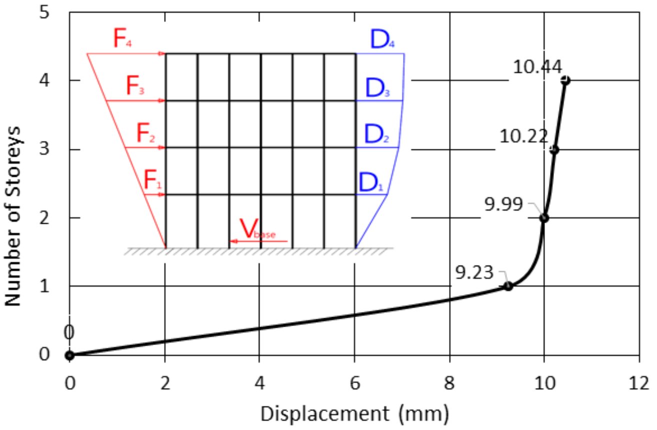


Figure 30. Building drift after retrofitted using chevron brace in longitudinal direction (V=96 ton).

Finally, failure occurred in the infill walls in the first storey as shown in Figure 31. It is noted that the base shear for the building after retrofitting using chevron brace increased by about 55% when compared to the base shear for the original building and increased by about 108% when compared to the base shear for the open ground floor suggestion.

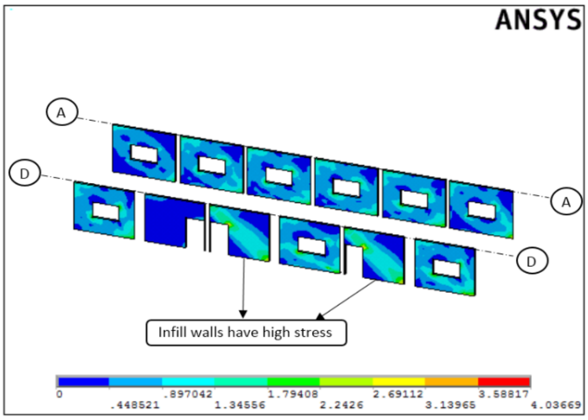


Figure 31. Stresses in infill walls in first storey.

Base shear values of the buildings in longitudinal direction are shown in Figure 32, for all analysed cases.

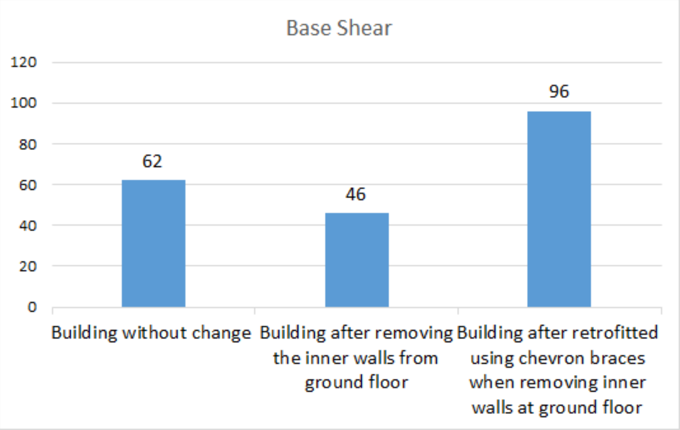


Figure 32. The base shear of the buildings in longitudinal direction.

6 CONCLUSIONS

In this paper, an old school building, typical of that used prior to 1989 in Egypt, was evaluated under earthquake loads in both longitudinal and transverse directions. It was found that the building is not safe in accordance to the current Egyptian design code in both directions. Therefore, the building was retrofitted by steel bracing in the ground storey. The building was retrofitted by knee braces in the transverse direction that satisfied design code provisions. For the longitudinal direction, it was retrofitted by a chevron braces and the building also became safe. This retrofitting scheme was the economist solution for the building. The fully open ground storey case was investigated as many schools in Egypt need this solution to provide space for students' activities. The following remarks are made based on the obtained results:

- Retrofitting the school building as proposed produced a much-improved seismic response, and allowed removing the undesirable ground story weakness.
- The proposed retrofitting scheme could indeed save a building with open ground story from collapse or heavy damage by probable future earthquakes.
- According to school owners, the partial strengthening of the building, which affected the open ground story only, is perhaps the only retrofitting possibility acceptable due to: (1) low execution costs; and (2) possible usage of the building during retrofitting work.
- Infill walls at the ground floor were the first elements to fail. Besides, it is shown that the best place to locate a door in an infill wall is in its middle.
- Retrofitting buildings with open ground floor to alleviate the undesirable soft story behaviour can be efficiently done using steel bracings.
- The research suggests an economical and practical solution for old school buildings in Egypt and other developing countries.

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