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Discrete Element Modelling of Masonry Infilled Steel Frames with Multiple Window Openings Subjected to Lateral Load Variations

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Abstract: Steel framed structures are routinely infilled with masonry or concrete walls. The infill offers in-plane shear resistance that adds to the one from the steel frame. However, the stiffness effect on the entire frame's response is usually neglected. In recent years, researchers have recognised the lack of in-depth understanding on infilled steel frames; hence specialised computational tools have been developed to provide an easy way of assessing these interactive structural systems and aid practising engineers in evaluating the overall behaviour.

A computational model to study the behaviour of masonry infilled steel frames for the non-standard case of variable potential positions of openings and their interaction, when subjected to in-plane monotonic loading, is herein developed. Using the Discrete Element Method (DEM) and the software UDEC, the masonry wall is modelled as an assemblage of distinct deformable blocks while the mortar joints as zero thickness interfaces. The numerical model validated against full scale experimental tests found in the literature and a good agreement obtained. In addition, a series of parametric studies were performed to draw the significance of the size and location of the openings on the lateral load capacity, as well as the stiffness and failure mechanisms of the infilled steel frames. From the results analyses, it was found that the inclusion of multiple openings significantly reduces the strength and stiffness of the system. In particular, placing an opening close to the point of application of the lateral load will result to further reduction of masonry infill's stiffness.

Keywords: Computational analysis, crack patterns, DEM, infill, masonry walls, openings, steel frame, stress tensors.

INTRODUCTION

Structural frames, constructed either by steel or reinforced concrete (RC) are often infilled with masonry panels. It is common practice in design to completely disregard their existence; a main reason for this is the actual complexity of the system, while its behaviour is not fully understood yet. Therefore, in practice, the panel and the frame of the structure are designed separately ignoring their interaction effects. What is often unknown to design engineers is that the two components complement each other. Despite research dating back to the 1950s, there is still lack in understanding of the interaction behaviour of masonry infilled steel frames which deem further investigation. Research works have been carried out through both full-scale experimental testing and various types of computational analyses in order to gain a better understanding and representation of the detailed behaviour (i.e. crack patterns) of such systems. With technological advances, there has been a significant development in computational software which is used for the research of such structural systems and they become increasingly popular due to large costs associated with full-scale experiments and data acquisition systems required to gather all the necessary information. There are often uncertainties over the accuracy of the computational models; therefore previous experimental tests provide confidence to validate the model. Once this barrier is overcome, a range of variables and parameters is worth to be examined to build knowledge on the mechanical behaviour of the materials and this complex interacting system itself.

It is well accepted that masonry infill walls affect the strength and stiffness of infilled frame structures (either made of RC or steel). Particularly, designing structures in seismic areas while ignoring the frame-infill panel, the capacity of the frames is underestimated under lateral loads, since infill walls increase the stiffness dramatically by acting as a compressed diagonal 'strut-model' area. This results a possible change of the seismic demand due to the significant reduction in the natural period of the composite structural system [1, 2]. The main reason for neglecting the infill wall effect is for the sake of simplified calculations, while it is partly attributed to incomplete knowledge of the "composite" behaviour of the frame and the infill, as well as due to the lack of conclusive experimental and analytical results to substantiate a reliable design procedure for this type of structures, despite the extensive experimental works [3-7] and analytical investigations [8-22]. So far, it is well understood that an infill wall acts as a diagonal strut connecting the two loaded corners under lateral loads; an approach that is only applicable in the case of infill walls without openings (eg. doors, windows, etc.) which interfere the diagonal distribution of stresses. Moreover, so far, researchers [23-28] investigated the significance of the opening size, by introducing an updated macro-model of infilled frames along

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using reduction factors. However, the location of the opening in infilled frames has not been extensively investigated yet.

The aim of this paper is to draw the significance of the opening(s) position on the lateral load carrying capacity, stiffness and failure mechanism of an infilled steel frame. A computational model to study the non-linear interaction between the masonry infill and the steel frames subjected to in-plane monotonic loading is developed. A series of parametric scenarios was examined to obtain the impact of the variability of the opening position, number of opening and load condition onto infilled steel frames.

DISCRETE ELEMENT MODELLING

The Discrete Element Method (DEM) falls within the general classification of force-based numerical method for discontinuum analysis techniques. It is presented in the UDEC (Universal Distinct Element Code) software, developed by Cundall in the early 1970s [27]. The method was originally used in rock engineering projects where continuity between the separate blocks of rock does not exist [28]. Recently, UDEC has been used for simulating the mechanical behaviour of masonry structures [29-35]. The Universal Distinct Element Code (UDEC) is a numerical program based on DEM for discontinuous modelling and can simulate the response of discontinuous media subjected to either static or dynamic loading. When used to model masonry structures, the masonry units are represented as an assemblage of either rigid or deformable discrete blocks. The former ones do not change their geometry as a result of any applied loading and are mainly used when the behaviour of the system is dominated by the mortar joints, whereas the latter ones may take any arbitrary geometry. Deformable blocks are internally discretised into Finite Difference triangular zones and each element responds according to a prescribed linear or non-linear stress-strain law. These zones are continuum elements as they occur in the Finite Element Method (FEM). Mortar joints are represented as zero thickness interfaces between the blocks. The interfaces can be viewed as the interactions between the blocks and they are simulated employing the appropriate stress-displacement constitutive laws. The interaction between the blocks is represented either by a set of "point" contacts or by a set of "edge-to-edge" contacts (without attempt to obtain a continuous stress distribution through the contact surface). Based on the Mohr-Coulomb failure criterion, the mechanical interaction between the blocks is simulated at the contacts by spring-like joints with normal (JKn) and shear stiffness (JKs) as well as frictional (Jfric), cohesion (Jcoh), tensile (Jten) and dilation (Jdil) characteristics. As with FEM, the unknowns are the nodal displacements and rotations of the blocks. However, unlike FEM, the unknowns in the distinct element method are solved explicitly by differential equations from the known displacement while Newton's second law of motion gives the motion of the blocks resulting from known forces acting on them. So, large displacements and rotations of the masonry blocks are allowed with the sequential contact detection and update of tasks automatically. This differs from FEM where the method is not readily capable of updating the contact size or creating new contacts. Convergence to static solutions is obtained by means of adaptive damping, as in the classical dynamic relaxation methods.

EXPERIMENTAL TESTING

The experimental test of a solid masonry infill frame (WC7) carried out by Dawe and Seah has been used for the validation of the computational model. Fig. (**1**) shows the test set up including the loading system. The dimensions of the infill masonry wall panel tested were 3,600 mm long by 2,800 mm high. The wall panel consisted of concrete masonry units with dimensions 200×200×400 mm placed in a running bond. The average compressive strength of the masonry concrete blocks was 30 MPa. The mortar used was made of 1:9 (OPC:sand). The moment resistant steel frame fabricated using a W200×46 beam and two W250×58 steel columns.

The specimens were tested upon a W310×52 supporting beam. Horizontal load was applied incrementally at the top left hand corner of the frame. Load increments of 22.2 kN were applied to the specimen. The panels were inspected visually for signs of cracking at each load increment. Also, the magnitudes of displacements at the top left hand corner of the panel were recorded. From the results analysis, it was found that major cracks initiated at a load of 310 kN while the maximum lateral load observed at 534 kN.

COMPUTATIONAL MODELLING OF MASONRY INFILL STEEL FRAMES

Geometric models that represent the infill wall panel tested in the laboratory were created in UDEC (Fig. **2**). Each concrete masonry unit was simulated by a deformable block separated by a zero thickness interface at each mortar joint. To allow for the dimensions of mortar joints in the wall panel tested in the experiment, each deformable block was increased in size in each face direction. The interface's stiffness is deduced from the stiffness of the real joints. Blocks modelled as inelastic deformable behaving according to a Mohr-Coulomb plasticity model. The mortar joints represented as zero thickness interfaces and modelled using UDEC's Coulomb slip-joint area contact with residual strength. The steel frame components in the model were simulated as isotropic elastic material to promote the masonry infill's cracking mechanism. Tables **2** to **4** show the material parameters for the constitutive models. Such material parameters have been obtained from [38-42]. Also, the coefficient of friction between the steel components and masonry panel has been taken equal to 0.25 [41]. The bottom part of the wall panel was modelled as a rigid support, while the vertical edges of the wall panel were left free. The self-weight was incorporated as gravitational load.

Initially, the model was brought into a state of equilibrium under its own self-weight. Then, a monotonic horizontal load was applied on the top left corner of the panel to replicate the situation occurred in the experiment. Load applied at increments of 22.2 kN, similarly to the experimental test. At each load increment, the horizontal displacement at the top left hand corner recorded.

Fig. (**3**) compares the experimental load-displacement relationship against that predicted from the computational model. Fig. (**4**) compares the experimental against the computational crack patterns obtained from UDEC. Good correlation was obtained between the numerical and experimental

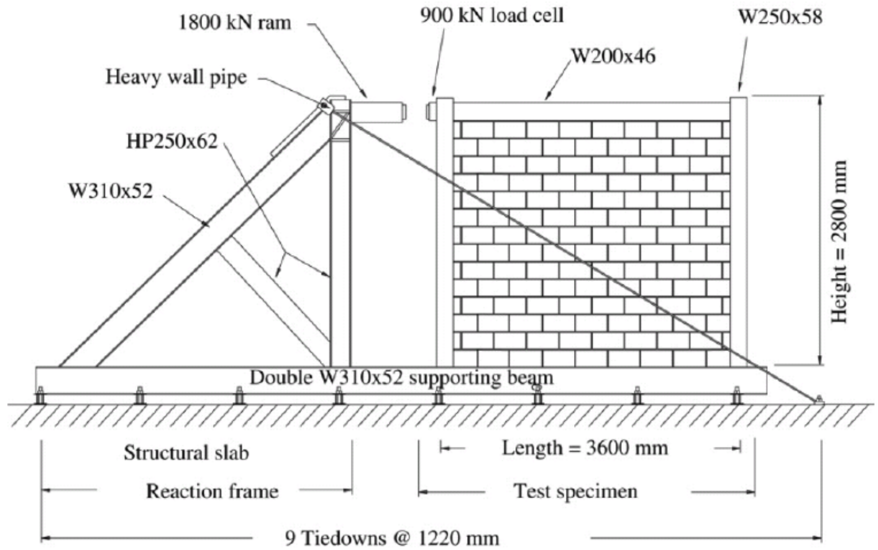


Fig. (1). Experimental test set up including the loading system [38].

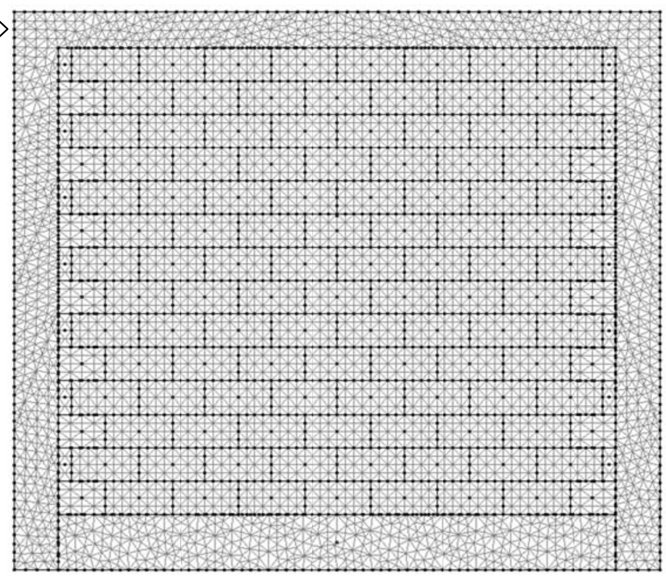


Fig. (2). The mesh at the UDEC model.

results. As can be observed from Fig. (**3**), the stiffness and strength that the panel can carry predicted by UDEC compares well with that obtained from the experiment. The crack pattern was also very similar to the behaviour observed in the laboratory. Large stresses propagate from the top left hand corner where the load is applied to the diagonally opposite corner of the steel frame (Fig. **4b**). The aforementioned stresses correspond to the double strut failure mechanism whereby separation of the masonry unit blocks occurred in these regions.

EFFECT OF WINDOW OPENING ON INFILLED FRAME CAPACITY

The effect of the multiple window openings on the infilled frame capacity has also been examined. Three different geometric configurations were undertaken where the size of the windows remained the same while the position of multiple openings varied (Fig. **5**). The size of the opening was assumed to be 1.2x0.8 m (width x height), which corresponds to 15% opening of the solid wall. No lintel has been assigned at the top of the window openings with scope to simulate the worst case scenario of many existing low to medium rise masonry buildings in the UK [43]. The load was applied at the top left hand corner of the frame. Comparisons made with respect to the load against the displacement relationships, the load capacities for each specimen, the deformations and the stresses at particular areas within the panel.

Strength and Stiffness of Masonry Infilled Frames

Fig. (**6**) demonstrates the load-displacement profiles for each of the four specimens. It is observed that the stiffness of the solid wall is different to that of the wall panels with openings. All three specimens with openings behave similarly up to the load level of 225 kN while their behaviour differentiates at the latter part of the load-deflection curves towards yielding. A comparison between the load capacities is synopsised in

Table **4**. As expected, the presence of openings significantly reduces the stiffness of the panel. Specimen W3 has the highest initial stiffness, whilst specimen 2 has the lowest one. This suggests that when an opening is positioned close to the corner of the portal frame where the load is applied, the overall stiffness of the system is reduced. The fact that the specimens W1 and W2 experience similar stiffness, it further reinforces this behaviour. Moreover, as the stiffness is decreasing, the load that the masonry infill steel frame can carry is also reduced. Similar results were found for the load capacities, with specimen W3 having the highest value of λ_m, where λ_m is a ratio between the load capacity of the panel containing openings and the one for the panel without openings. This again suggests that panels without openings positioned close to the application of the load achieve higher stiffness and strength. The lateral displacement at the ultimate load was also measured and presented in Table **4**.

Table 1. Input properties for the steel sections.

Properties	Unit	Value
Mass density	kg/m^3	7850
Bulk Modulus	GPa	139
Shear Modulus	GPa	79
Poisson's ratio	-	0.26
Young Modulus	GPa	200

Table 2. Input properties for the masonry units [38].

Properties	Unit	Value
Mass density	kg/m^3	1750
Bulk Modulus	GPa	17.2
Shear Modulus	GPa	12.9
Friction angle	Degrees	54.2
Cohesion	MPa	3.83

Table 3. Input properties for the mortar [36-38, 40].

Properties	Unit	Value
Joint normal stiffness	GPa/m	38.1
Joint shear stiffness	GPa/m	17.5
Joint friction angle	Degrees	35
Joint cohesive strength	MPa	0.6
Joint tensile strength	MPa	0.44
Joint dilation angle	Degrees	12
Joint residual cohesive strength	MPa	0.154
Joint residual tensile strength	MPa	0
Joint residual friction angle	Degrees	6.87

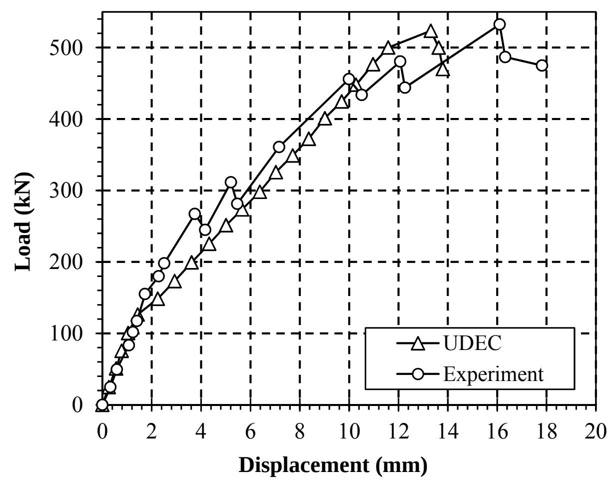
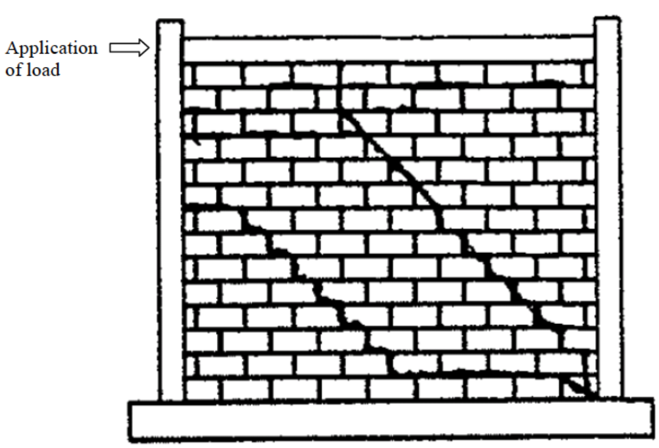


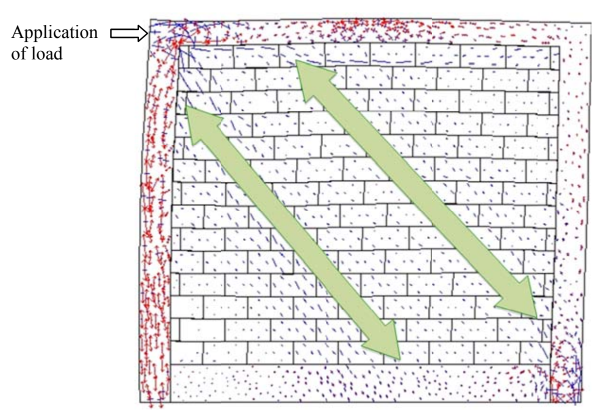
Fig. (3). Load-displacement profile for UDEC and experimental tests.

Failure Mechanisms of the Masonry Panel

The failure mechanisms of the infills with multiple window openings have also been investigated. The first visible cracks within the masonry panel of specimen W1 occurred at



(a) Experimental crack pattern [38].



(b) Principal stress tensors at the solid wall obtained from UDEC

Fig. (4). Comparison of experimental against computational results.

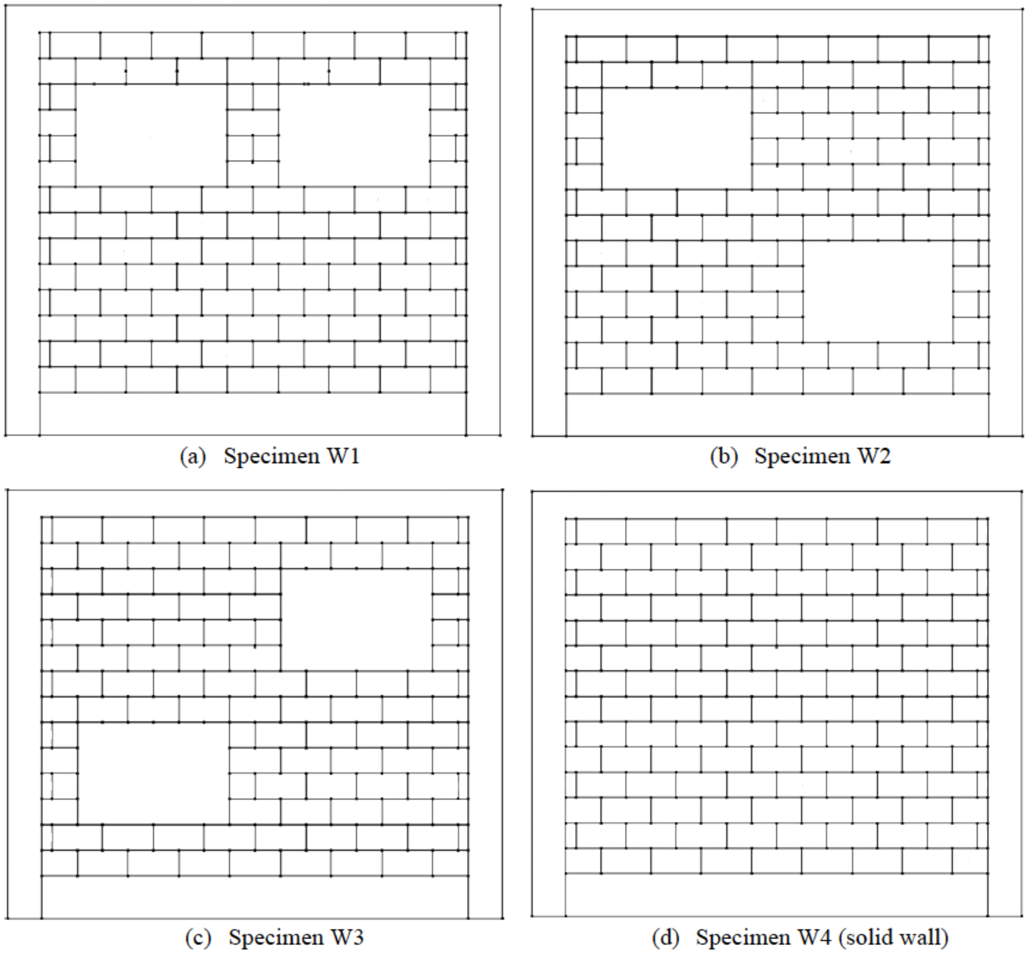


Fig. (5). Configuration of the masonry wall panels.

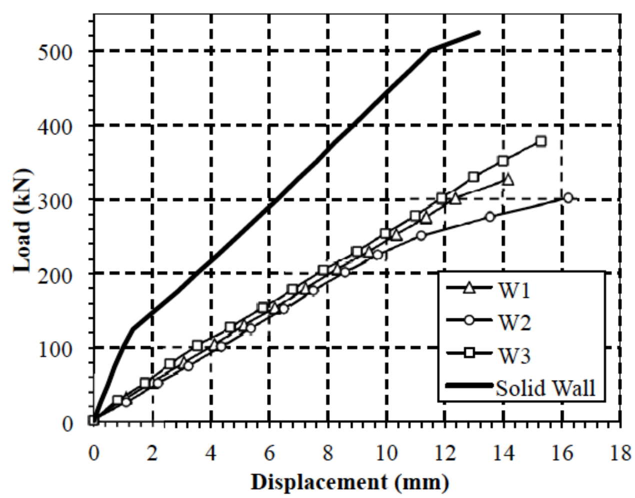


Fig. (6). Lateral load-displacement profiles for each specimens.

250 kN in the region illustrated by the circle in Fig. (**7a**). When the specimen was loaded further, cracking appeared along the direction of the arrows as well as above the two openings. Fig. (**7b**) depicts the horizontal displacement vectors at the last converged loading point of the analysis. It is worth to note that beyond the last converged loading point excessive displacement acquired in the masonry infill with significant lower strain hardening. Stresses are concentrated around the openings particularly in the areas above the windows. The development of two compression struts within the masonry was also observed and represented with arrows in Fig. (**7c**). Along these diagonals areas, large stresses propagate and cracking occurred. This separation is better illustrated in the enlarged detail in Fig. (**7a**). High stress concentration found in the loaded corner of the frame and the diagonally opposite right bottom corner which could cause

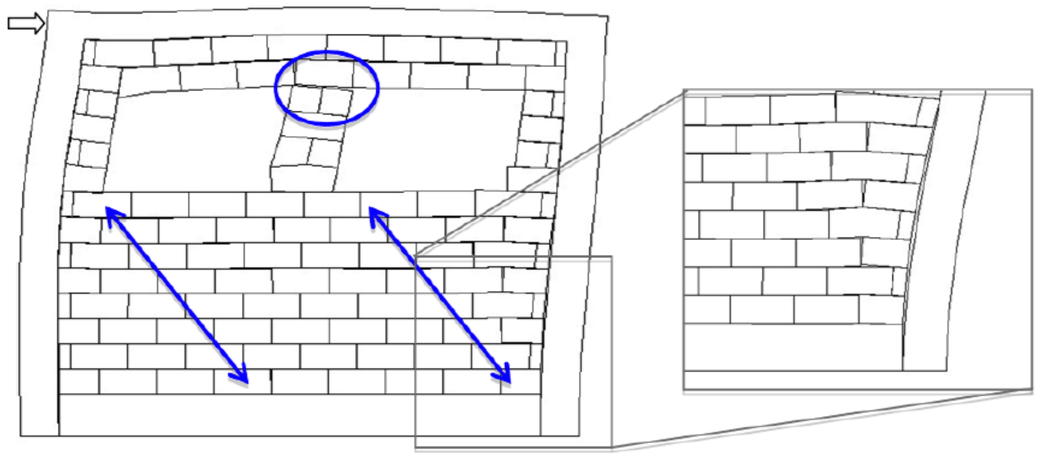
localised failure of the units in the vicinity of these areas. The significant drift of the left hand steel column was evident of the large loss of strength of the system. The strength of the system relies heavily on the leeward column. Hence, the presence of the openings causes a significant reduction in strength and stiffness at the top part of the masonry panel causing large deformations.

Table 4. Results for all specimens.

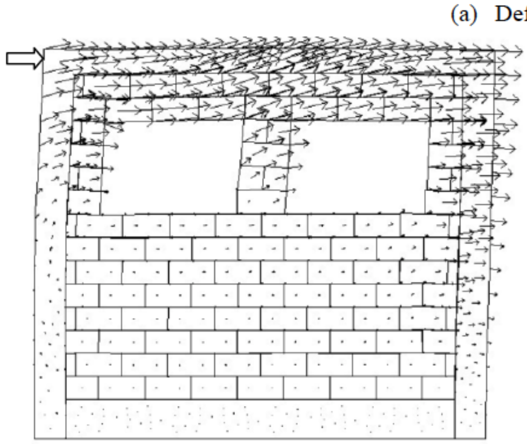
Specimen	Load (kN)	Lateral Displacement (mm)	Strength λ_m
W1	325	14.2	0.619
W2	300	16.2	0.571
W3	375	15.3	0.714
W4 (Solid Wall)	525	13.2	1.000

For the specimen W2, the load of the first crack was found to be around 225 kN and it was noticeable above both window openings. The most intense cracking occurred was the diagonal cracking formed to the right of the top left window opening (Fig. **8a**). The large lateral displacements found in this region promoted the bricks to separate along a compression diagonal strut which was formed due to the particular position of the openings. This diagonal strut then reaches the top edge of the opening on the right which causes the bricks above the window to displace in the y-direction (circled area in Fig. **8a**). The vectors in Fig. (**8b**) show the displacement of the masonry blocks in the horizontal and vertical direction. Similar cracking was also observed at the specimen W1. Fig. (**8c**) illustrates the principal stress zones of the masonry infill panel. It is observed that there are two main areas of diagonal compressive stress.

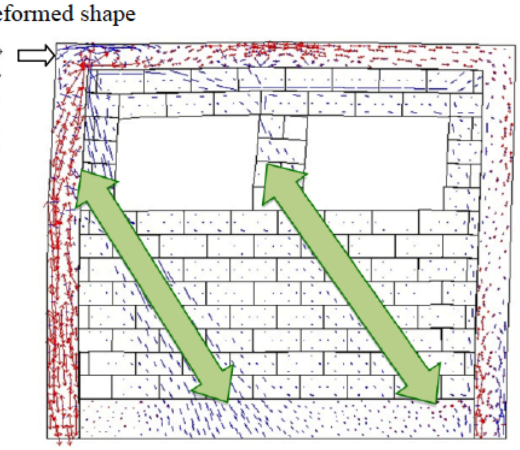
Fig. (**9**) illustrates the failure mechanisms of specimen W3. A similar failure mode to that of the solid wall is evident with just one compression zone formed by the cracking lines (Fig. **9a**). This is also apparent in Fig. (**9b**) which demonstrates the stress tensors as a result of the load. As, it was aforementioned this specimen has the highest strength amongst the three examined new specimens. It is, therefore, acceptable to suggest that the number of diagonal compression zones has an effect on the load capacity of the system. For example, specimens W1 and W2, contained two or more compression struts, causing a reduction in the strength of the masonry infilled steel frame. As stresses propagate predominantly along the diagonal direction, they also accumulate



(a) Deformed shape



(b) Displacement vectors



(c) Principal stress tensors

Fig. (7). Specimen W1 at a load of 325 kN.

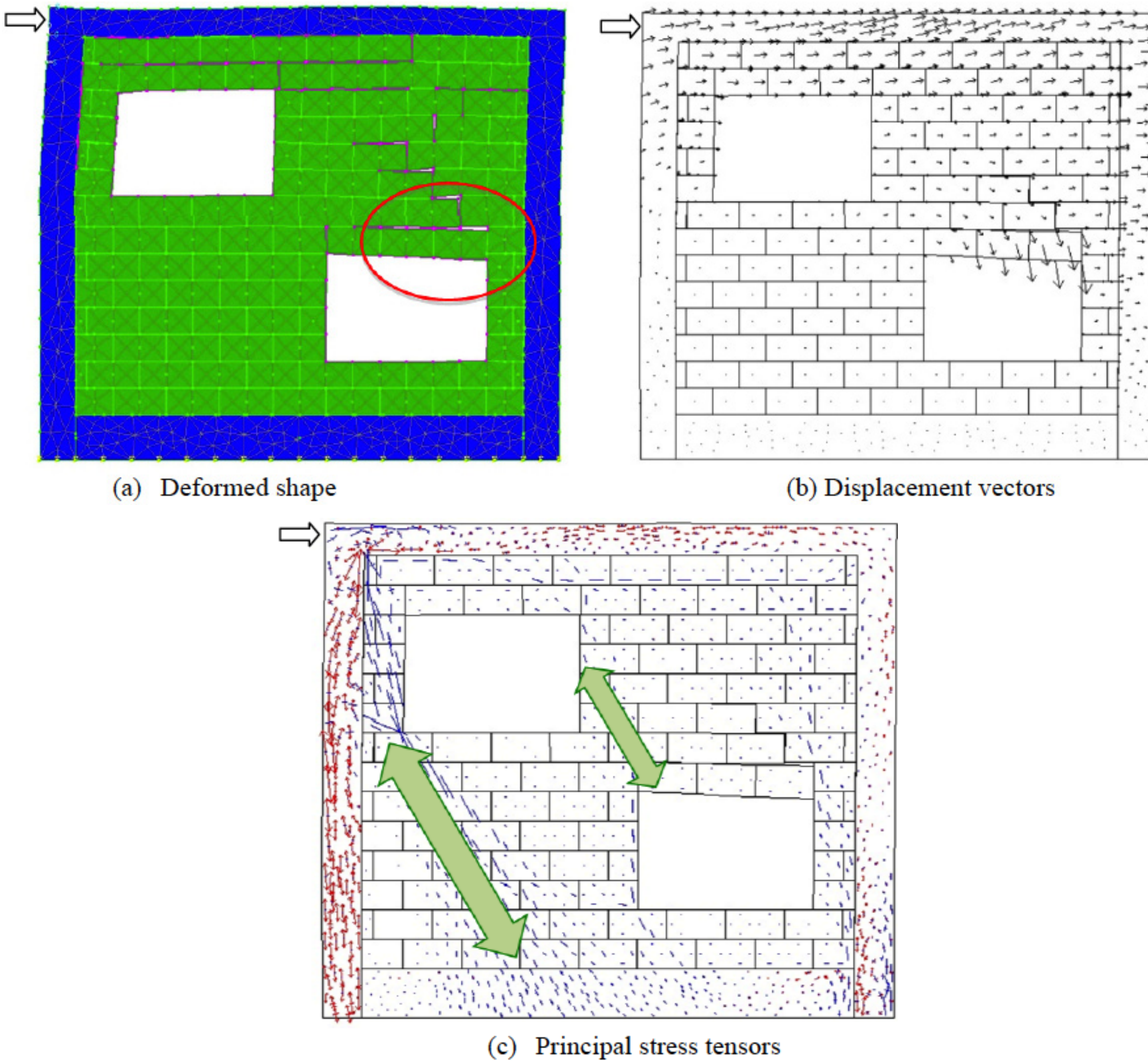


Fig. (8). Specimen W2 at a load of 300 kN.

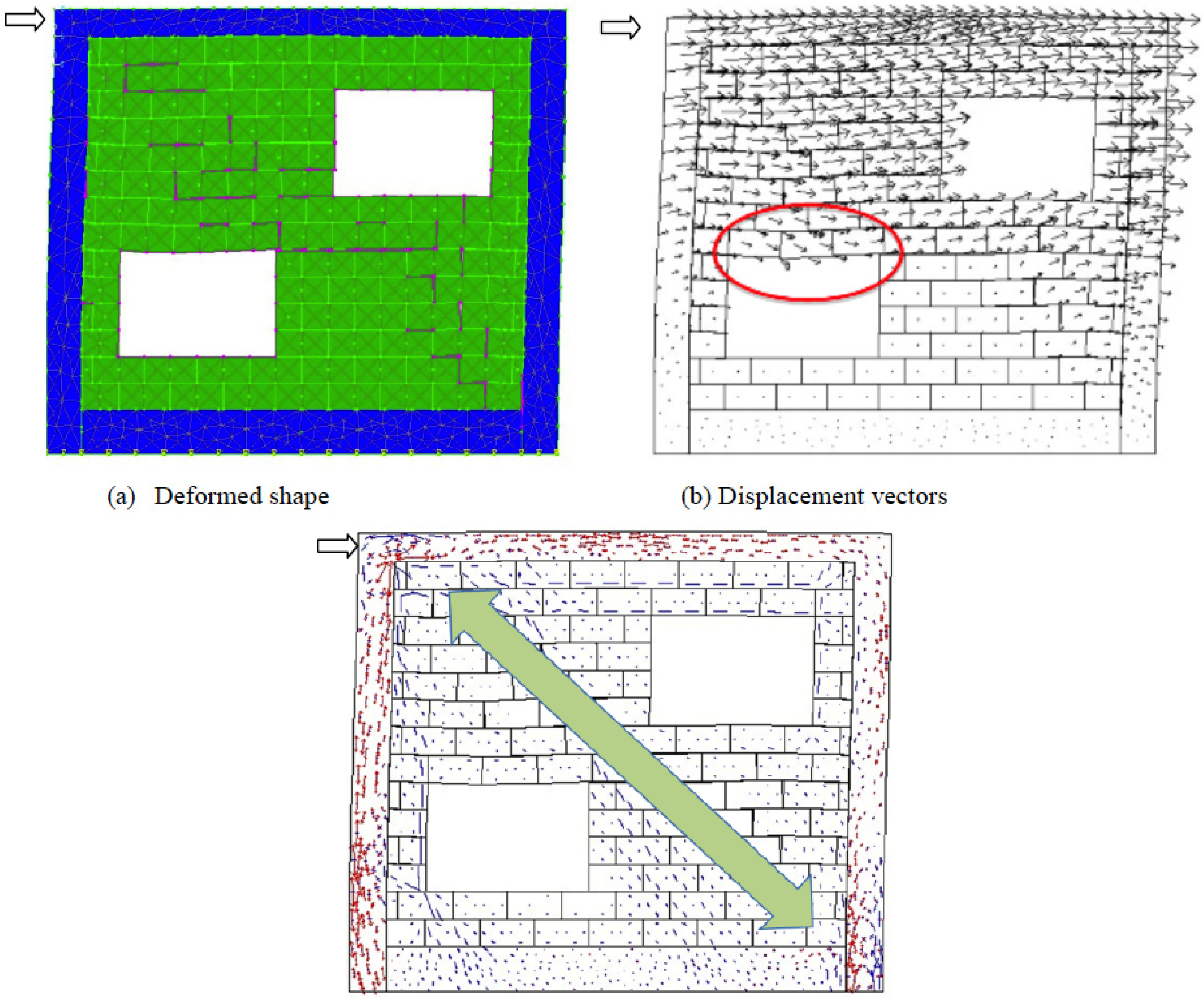
around the window openings which ultimately lead to further cracking at higher loads. In addition, Fig. (**9c**) depicts the displacement vectors, showing similar patterns to the previous models, with large displacements occurred at the top part of the masonry infill. Furthermore, at Fig. (**9b**), the circled area indicates the location where large displacements of the blocks occurred.

EFFECT OF LOADING CONDITION ON STEEL FRAMES

The effect of the actual loading type on the steel frame has been investigated by evaluating the responses of two lateral load conditions. The first case was the typical point load on the top left hand corner of the steel frame (Fig. **10a**), as used in all previous analyses presented in this paper, while the second case considered a lateral uniformly distributed load at the left hand column of the steel frame (Fig. **10b**). Comparisons made with respect to the strength and stiffness of the infilled system as well as their failure mechanisms, in order to draw the main differences and provide better understanding for such cases where, for instance, another frame is in full contact and distributes lateral loads.

When the point load was applied on the steel frame, the initial stiffness was relatively high. However, after a certain load (approx. 125 kN) the stiffness reduced and kept constant up until the failure of the masonry infill panel. On the other hand, the strength of the masonry infill steel frame is lower when the distributed load applied on the steel frame. The main reason resulted this behaviour is that the distributed load applied on the entire column, hence it deflects more affecting the bottom part of the infill, which now deforms severely, leading to higher overall displacements. When a point load applied to the masonry panel, the corresponding load capacity observed was 535 kN; the corresponding capacity for the case with the distributed load was 450 kN.

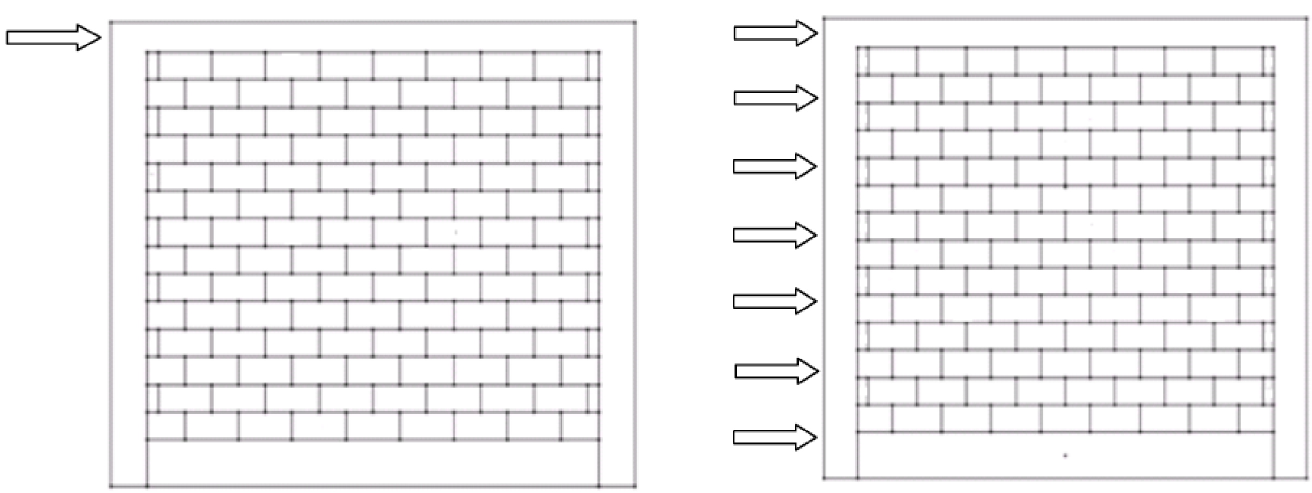
Figs. (**12** and **13**) compare the cracking patterns observed in the specimen with the solid wall when a point load and a uniform distributed load applied. The first signs of cracking for the masonry infilled steel frame subjected to point load occurred between the masonry and the steel frame towards the top corner at the loaded side of the frame due to significant bending of the column. For the case that a distributed load is applied, first cracking occurred at a lower height of the loaded column. Thereafter, stepped cracking patterns



(a) Deformed shape (b) Displacement vectors

(c) Principal stress tensors

Fig. (9). Specimen W3 at a load of 375 kN.



(a) Point Load (b) Uniformly Distributed Load.

Fig. (10). Configurations of load applied to the panel.

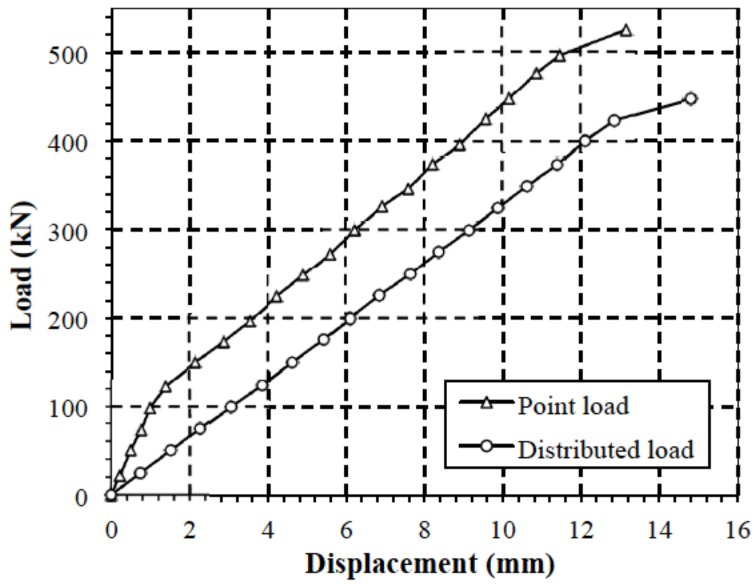


Fig. (11). Load displacement behaviour for both loading conditions.

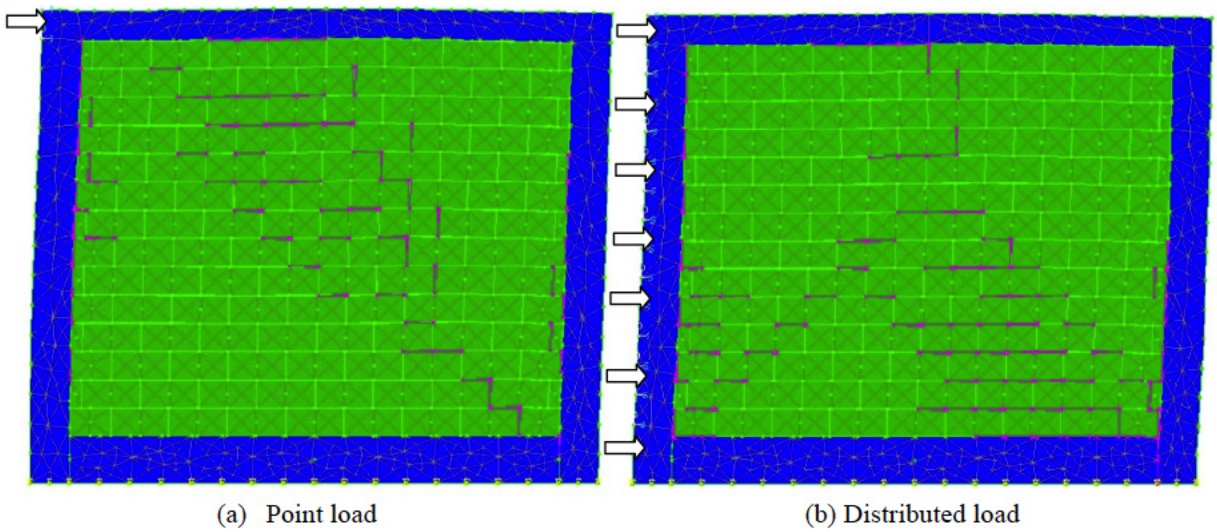


Fig. (12). Cracking observed in the solid wall when (a) point load (b) uniformly distributed load applied.

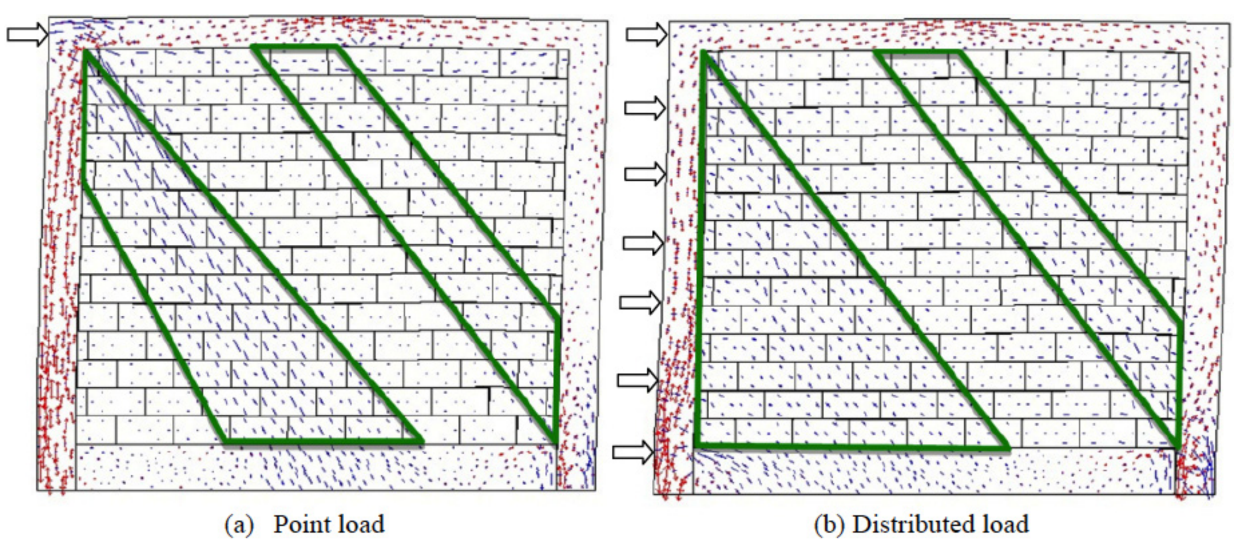


Fig. (13). Principal stress tensors for the solid wall when (a) point load, (b) distributed load applied.

formed in the bottom right part of the masonry panel while very little cracking occurred in the top left hand corner. Some cracks at the top part of the masonry panel, as shown in Fig. (**12**), formed only at very high loads. It is apparent that the compression diagonal strut-model which connects the loaded corner to the diagonally opposite corner is not formed anymore in the case of the uniformly distributed load. Fig. (**13**) highlights the principal stress tensors for the two models. It is observed that they are two main compression zones, however, the specimen subjected to the distributed load has been affected more significantly and this has led to the greater overall deformation of the frame. Similarly, the stresses in the steel frame are different, with large stressed areas concentrated in the base of both columns (Fig. **13a**), while a more uniform stress pattern found in Fig. (**13b**).

CONCLUDING REMARKS

This paper emphasizes and creates awareness of the behaviour discrepancy of infilled steel frames, with similar percentages of openings, but different multiple openings' positions as well as load conditions. A two dimensional discrete element model has been developed for the non-linear analysis of masonry infilled steel frames with multiple window openings. Each masonry unit was modelled separately with the mortar joints represented as "zero" thickness interface able to simulate crack propagation and sliding in the joints. Initially, the model has been validated against an experimental test obtained from the literature. The developed model was used in a series of sensitivity studies to explore the effects of multiple window openings arbitrary located in the masonry panel. Results compared with respect to the strength, stiffness and failure mechanisms of the steel frame.

From the results analysis, it is found that significant reduction of the strength and stiffness occurred when multiple windows used. In particular, when an opening is positioned close to the applied load, the overall strength and stiffness of the wall panel reduces. The application of a horizontal load, results a diagonal cracking in the masonry panel. The effect of the multiple windows and their position has a direct impact on the number of diagonal compression strut-model areas. It is established that, when fewer compression struts-model areas developed, the higher the strength and stiffness that the system are. The effect of loading conditions at the steel frame has also been studied. Moreover, it is revealed that by changing the load condition from a point load to a uniformly distributed load, the initial and the overall strength and stiffness was reduced. It is now recommended to further expand this study and investigate the effect of multiple openings with various positions and compare to infills with only one window/door but the same percentage of opening.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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