Journal of Engineering and Applied Sciences 2 (5): 930-943, 2007

An Investigation of the Behaviour of Steel Frames with Masonry Infills under Lateral Loading

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Abstract: Frame systems are commonly used in structural design. In the design and analysis of these types of structures, beams and columns are essential. Since no practical and generally recognized method has yet been developed, non-structural components such as, architectural walls are not usually taken into consideration in the analyses. On the other hand, the real structure may exhibit a different behavior than that of bare frames under lateral loadings such as earthquakes. This study describes the use of finite element method to asses the contribution of the infill to the behaviour of infilled steel frames. The influence of masonry infills on the behaviour of steel frames is studied experimentally and analytically by using a finite element model to simulate the behaviour of infilled steel frames subject to lateral loads. New material models are proposed for masonry infill (no plaster) and plastered masonry infills. The model is verified by comparison with laterally tested infilled frames. The validity of results is checked with the experimental results. Steel framing is chosen, due to fact that its mechanical behaviour is rather well known with respected to reinforced concrete structure. Besides the fully infilled steel frames, partially infilled frames are also tested and analyzed. The infill is modeled with, well-known, diagonal strut analogy also with shell elements. A new modeling proposal, with the use of nonlinear springs is also introduced in the study. The proposed analyze method is based on adjustment or calibration of Young Modulus of infill frame material. At the results, experimental lateral load vs deflection curves are compared with analytical ones.

Key words: Partially in-filled steel frames, steel frames, nonlinear FEM analysis, ANSYS

INTRODUCTION

In steel and concrete moment frame construction, infilling some of the bays with walls made of masonry units is a common practice in many countries (Aliaari and Ali, 2005). Masonry can be considered as a composite material built of brick units and mortar joints. Since they are usually considered as non-structural elements, their interaction with the bounding frame is often ignored in the design (Mehrabi and Shing, 1997). Neglecting the presence of infills in the calculation of structures subject to horizontal loads leads to an evaluation of stresses in the frames which is often far from the real situation and may compromise safety (Papia, 1988).

The significance of infilling frames in determining the actual strength and stiffness of framed buildings subject to lateral force has long been recognized (Saneinejad and Hobbs, 1995). When a structural frame of a building is infilled with masonry, which is both stiff and strong in diagonal compression, the diaphragm action of the wall induces a substantial increase in the lateral stiffness of the structure (Riddin). In conventional design practice, the stiffness of such walls is usually neglected, and this could result in a larger calculated fundamental period of the structure and smaller seismic code based lateral loads (Memari *et al*., 1999).

There are still some unresolved aspects in the evaluation of the behaviour of unreinforced masonry buildings and we are still far from having reliable tools for predicting the results of full scale experimental tests (Magenes and Calvi, 1997; Gambarotta and Lagomarsino, 1997a, b). There is a large number of parameters that take part in the mechanical behaviour of masonry: mechanical properties of brick and mortar, geometry of bricks, joint arrangement, etc. The evaluation of the influence of these parameters on the overall behaviour of a masonry panel is not simple (Gabor *et al*., 2006).

In recent years, there has been a steady interest in the mechanics of unreinforced masonry structures, with the aim to provide efficient tools for better understanding their complex behaviour (Milani *et al*., 2006). Studies on the structural behaviour and response of masonry infilled frames extended as early as the 1950's and continue to date. The interaction between the masonry infill and the

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bounding structural frame is complicated in view of the different deformational characteristics of the 2 components, in addition to the already complex behaviour of masonry itself which maintains unique characteristics such as the presence of vertical and horizontal mortar joints, solid versus hollow masonry units etc (Hakam, 2000).

Attempts at the analysis and design of infilled frames since the mid 1950s have led to several methods. However, the inclusion of infilling walls as structural element is not yet common (Saneinejad and Hobbs, 1995; May and Ma, 1985). One of the difficulties in predicting the behaviour of the composite frame is the realistic stress analysis of the masonry infill which is in a state of biaxial stress. The in-plane deformation and failure of masonry is influenced by the properties of its components, the bricks and the mortar. The influence of the mortar joints is particularly significant as these joints act as planes of weakness (Dhanasekar, 1986).

When an infilled frame is subjected to a lateral load, only for low values of horizontal load, the frame and infill behave in monolithic fashion. As the load increases the frame and infill usually separate over a large part of the length of each side and regions of contact remain only adjacent to the corners at the ends of the compression diagonal (Smith, 1967) the load is transferred by diagonal strut action within the masonry which results compression zone near the loaded corners and shear and normal stresses on the jointing planes in the interior of the panel. A local shear failure usually occurs near the center of the panel which then progress towards the loaded corners. If the frame is flexible, a corner crushing failure is observed on the contrary of stiffer frames where failure occurs as a continuous path of sliding and cracking of the infill down the loaded diagonal (Dhanasekar, 1986).

In 1960, Polyakov suggested the possibility of considering the effect of the infilling as equivalent to diagonal bracing and this suggestion was later taken by Holmes who proposed that the equivalent diagonal strut, having the same thickness as the panel, should have a width equal to one third of the diagonal length of the panel. This view was not shared by Smith (Mallick and Severn, 1967). He correlated the effective width with the length to height ratio of the frame.

Application of the finite element method to the linear analysis of frames with filler panels have been presented by Karamanski (1967), Lamar and Fortoul (1969), Natarajan and Wen (1970), King and Pandey (1978) and Pandey also developed a procedure based on FEM for analysing infilled framed structures. The static nonlinear analysis of RC frames with filler panels was reported by Franklin (1970) who used tie-link elements to represent the bond between the frame and wall elements. These links were assumed to fail when a predetermined level of bond stress was reached (Kost *et al.*, 1974). Mallick and Severn (1967), Liauw and kwan (1984) and Kwan and May and Ma (1984) used FEM for the analysis of 2D infilled frames. May and Naji (1992) carried out nonlinear analysis of infilled frames under monotonic and cyclic loadings using FEM. They modelled the skeletal frame with frame elements and panel is modelled with 8 noded isoparametric elements. Singh investigated the inelastic response of three dimensional RC frames with infills using FEM. Mehrabi and Shing (1997) all presented a method for modelling of masonry mortar joints and cementitious interfaces. A smeared finite element model is used to model the behaviour of concrete in frame and masonry units.

Wasti and Gülkan (1974, 1976) replaced the infill by a number of discrete linear springs as shown in Fig. 1. The masonry and mortar composite was modelled as a linearly elastic-perfectly plastic (no hardening) isotropic medium. This solution for a frame with full or partial infill gave acceptable agreement when compared with the experimental results of Fiorato *et al.* (1970).

Seah (1998) suggested a simplified macro model, in which the infill wall is modeled by an equivalent strut (a nonlinear diagonal spring) with force-deformation properties obtainable from testing or the micro model analysis. In the macro model, all frame joints are assumed pinned in order to obtain the stiffness contributed only by the brace element (Aliaari and Ali, 2005).

Lourenc and Rots (1997) considers the mortar joint as the weakest element of the brickwork, where all type of plastic deformation take place. The mortar joint is modelled by an interface element, using multisurface plasticity in order to describe compression, shear and tensile behaviour.

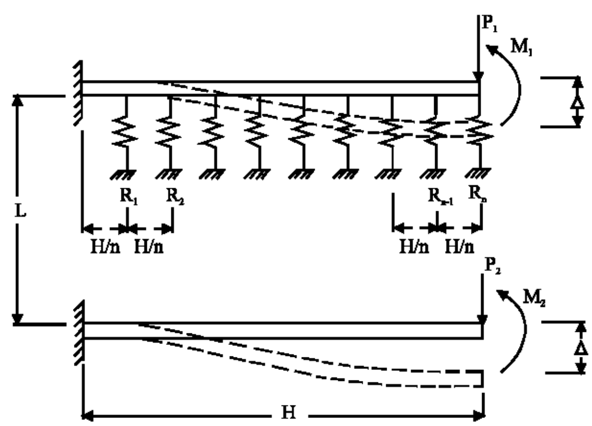

Fig. 1: Representation of infill with springs (Gulkan and Wasti, 1974, 1976)

Formica *et al*. (2002) presents a discrete mechanical model for masonry walls based on a Lagrangean description where each brick is described as a rigid body and each mortar joint as an interface element. The proposed approach is based on a discrete model of brick masonry walls where the bricks are depicted as rigid bodies and the mortar joints as straight interface elements.

Gabor *et al*. (2006) presents a numerical and an experimental analysis of the in-plane shear behaviour of hollow brick masonry panels. The non-linear behaviour of masonry is modeled considering elastic-perfectly plastic behaviour of the mortar joint. Experimental methodology consists in the diagonal compression of considered masonry walls.

El-Dakhakhni *et al*. (2003) proposed to model infilled steel frames. Instead of a single diagonal brace element, three brace elements are used to model the infill wall in order to take into account the contact length at corners during infill wall-steel frame interaction. In the ANSYS model, COMBIN39 elements are used to model the strut and BEAM3 elements of the ANSYS library is used to model the beam and column members. Beam-column connections are represented as trilinear rotational spring elements. The rotational stiffness of the springs is chosen in a manner that the lateral stiffness of the bare frame finite element model be equivalent to that of the actual bare frame, which can be determined experimentally or analytically (Aliaari and Ali, 2005).

Recently, studied the behavior of shear studs in steel frames with reinforced concrete infill walls. Xiangdong (2005) presented an experimental study of the cyclic behavior of a composite structural system consisting of partially-restrained steel frames with reinforced concrete infill walls.

In this study; an analytical procedure, based on macromodels adopted for depicting the nonlinear response of the infilled frames subject to in plane loads was proposed by utilizing a finite element analysis software. The developed model was verified using the experimental results of masonry infilled steel frames test results.

EXPERIMENTAL STUDY

In this study, the results of a theoretical and experimental investigation about the inelastic behaviour of infilled steel frames are described and a method of analysis using the FEM was developed. Initially an experimental program was conducted to understand the behaviour and contribution of masonry infills on the lateral load carrying capacity of steel frames. Therefore, an experimental program is conducted and 24 steel frames with masonry infills are tested (Koken, 2003; Kaltakci and Koken, 2003a, b; Korkmaz, 2004). The frames are made out of steel having channel sections. In order to prevent joint failure, rigid connections are constituted by welding. The cross-sectional properties of a typical frame are shown in Fig. 2. Also in Fig. 3, an illustrative drawing of tested specimens is exhibited. The proportional ratio of the infill is defined as H_m/H_f, where H_m is the height of the masonry infill and H_f is the height of the area which is enclosed with the frame. Proportional ratio is taken as one parameter for test specimens and three different proportion ratios, $H_m/H_f = 4/4$, $H_m/H_f = 3/4$ and $H_m/H_f = 2/4$ are determined. The material of the infill panel is chosen as another parameter which are; plastered and non-plastered clay brick walls and Autoclaved Aerated Concrete (AAC) walls. Also, bare steel frames, with no infills, are tested. The last parameter is length over height ratio of frame's (L/H_f). Three length over height ratios are chosen as

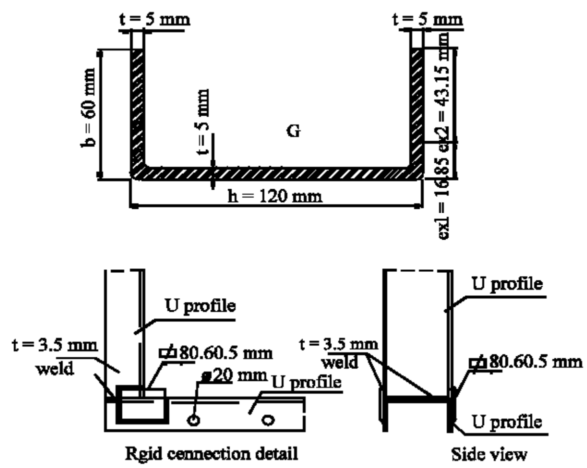

Fig. 2: The properties of the channel section used and the connection detail

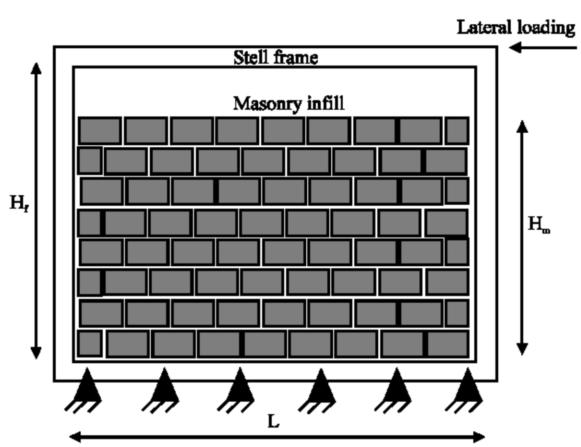

Fig. 3: Tested steel frame and infill wall

Table 1 Physical and geometrical properties of the specimens tested

Name of specimen	Type of infill	Frame length (L) (mm)	Frame height (H_f) (mm)	Infill ratio (H_m/H_f)
Without infill	No Infill	843.7	823.7	-
Non-plastered-L/H = 1-4/4	Brick wall	843.7	823.7	4/4
Plastered-L/H = 1-4/4	Brick wall+Plaster	843.7	823.7	4/4
Non-plastered -L/H = 1-3/4	Brick wall	843.7	823.7	3/4
Plastered -L/H = 1-3/4	Brick wall+Plaster	843.7	823.7	3/4
Non-plastered -L/H = 1-2/4	Brick wall	843.7	823.7	2/4
Plastered -L/H = 1-2/4	Brick wall+Plaster	843.7	823.7	2/4
AAC-L/H = 1-4/4	AAC	843.7	823.7	4/4
AAC-L/H = 1-3/4	AAC	843.7	823.7	3/4
AAC-L/H = 1-2/4	AAC	843.7	823.7	2/4
With no infill	No Infill	1643.7	823.7	-
Non-plastered -L/H = 2-4/4	Brick wall	1643.7	823.7	4/4
Plastered -L/H = 2-4/4	Brick wall+Plaster	1643.7	823.7	4/4
Non-plastered -L/H = 2-3/4	Brick wall	1643.7	823.7	3/4
Plastered -L/H = 2-3/4	Brick wall+Plaster	1643.7	823.7	3/4
Non-plastered -L/H = 2-2/4	Brick wall	1643.7	823.7	2/4
Plastered -L/H = 2-2/4	Brick wall+Plaster	1643.7	823.7	2/4
With no infill	No Infill	843.7	1603.7	-
Non-plastered -L/H = 1\2-4/4	Brick wall	843.7	1603.7	4/4
Plastered -L/H = 1\2-4/4	Brick wall+Plaster	843.7	1603.7	4/4
Non-plastered -L/H = 1\2-3/4	Brick wall	843.7	1603.7	3/4
Plastered -L/H = 1\2-3/4	Brick wall+Plaster	843.7	1603.7	3/4
Non-plastered -L/H = 1\2-2/4	Brick wall	843.7	1603.7	2/4
Plastered -L/H = 1\2-2/4	Brick wall+Plaster	843.7	1603.7	2/4

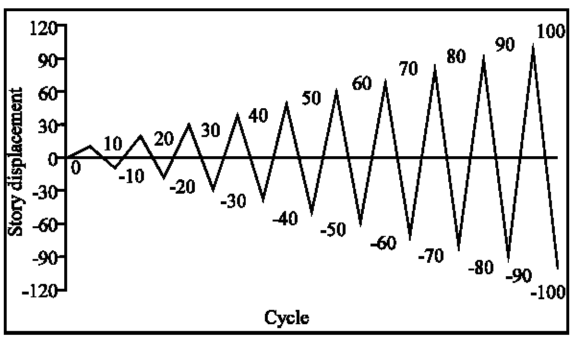

Fig. 4: Applied top story displacements

$L/H_f = 1$, $L/H_f = 2$ and $L/H_f = 1/2$. Frames infilled with AAC is tested just for length to height ratio (L/H_f) is equal to 1. The dimensions of the specimens are determined by scaling the full size frames approximately by 1/3. Therefore, a 3000×3000 mm frame is represented by a specimen with a size 843×843 mm. The wall panel has a depth of 85 mm. In Table 1, physical and geometrical properties of the specimens are summarized.

The loading scheme consists of displacement controlled reversed cyclic loading (Fig. 4). However, intended analyze type depends on monotonic lateral load vs. displacement curves of the infilled frames. Consequently, envelope curves of cyclic loading are used in the analyses. Applied maximum displacement is determined in accordance with the stroke capacity of the loading pistons. Actually it is not required to apply that much of displacement to the system since the masonry infill looses its stiffness at the preliminary stages of the loading scheme. The reason of that decision is to see formation of hinging in the steel bare frame for another push-over study.

FINITE ELEMENT STUDY

Finite Element (FE) models of the specimens tested are prepared and analyzed using a nonlinear analysis procedure of ANSYS, general purpose FEM software. ANSYS is commercially available and therefore it may be possible for other researchers to obtain it and regenerate the results of this study.

Developed FE models: Three different FE models are developed for infilled frames. For the first model, shell elements and 2D beam elements are used for infill wall and for steel frame, respectively. In order to simulate the separation of the wall from the frame contact elements, which transmits only compression forces, are placed between the frame and the wall (Fig. 5).

When mixing shell and frame elements, compatibility problems may arise at common nodes. The model did not contain any interface or link elements between shell and frame element nodes. This situation crates some calculation errors definitely. The steel frame may also be modelled with shell elements to overcome that problem. In order to see the error percentage, a specimen is modelled completely with shell elements and the other is modelled with frame-shell element combination. A linear analysis is conducted. The top displacement values are compared for a unit load. The error percentage

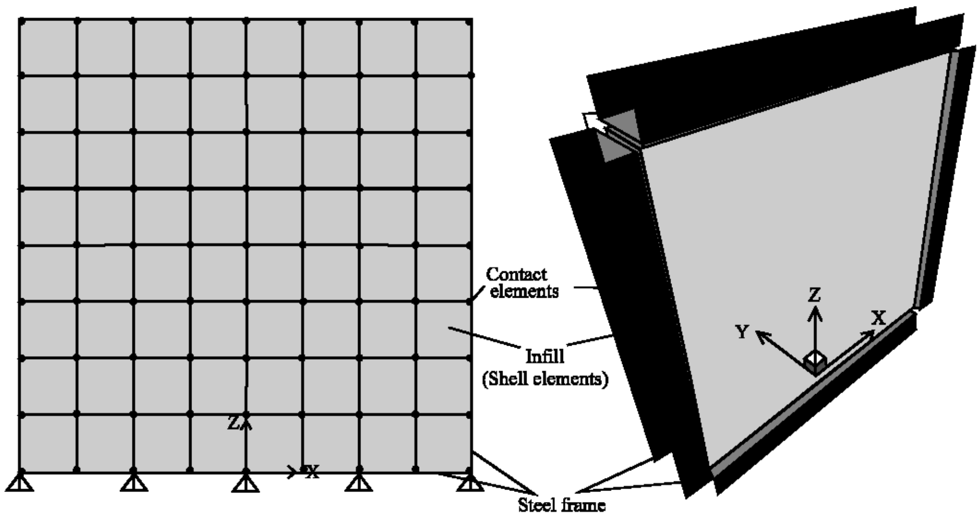

Fig. 5: Modelling of an infilled frame with shell elements

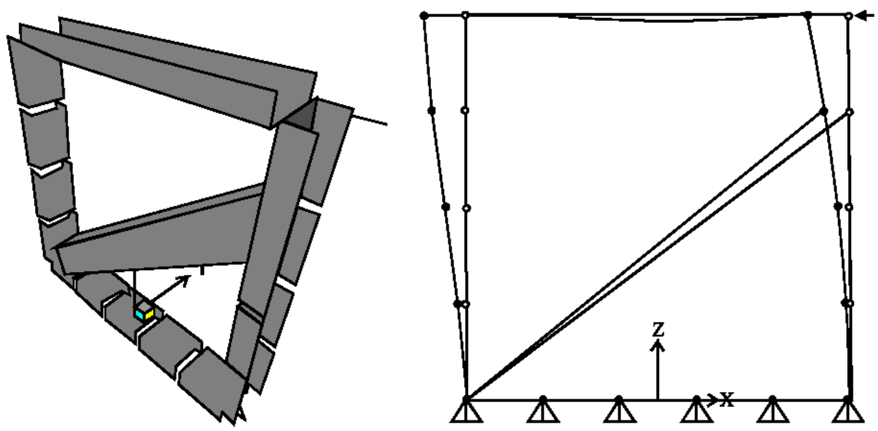

Fig. 6: Steel frame and diagonal-strut modelling

is on the order of 0.8%. considering the proposed method is an approximate method, that much of error does not constitute

For the second model, infill wall is modelled through a diagonal compression strut (Fig. 6) which is very common to represent infill contribution to the lateral load carrying capacity of the frame. Generally, fully infilled frames are modelled with this analogy. In this study, partial infills are also represented with diagonal struts. For partially infilled frames, one node of diagonal strut member is located on bottom corner of the frame and the other node is placed to the point where top of the wall intersects the frame (Fig. 6).

In the last model, infill wall is modelled with nonlinear springs (Fig. 7) (with the element type Combin 39 existing in ANSYS element library). This element is previously used by Hakam (2000) to represent the infill wall in the frame. But the loading was applied diagonally to the frame and also spring was placed along the diagonal. As a result, force was applied to the spring in its axial direction. In current study, both application of loading and placement of spring members are horizontal. The springs are placed along the contact length of wall and frame. Due to separation between the frame and the panel, the length of contact is taken as fraction, β, of the height of the infill wall. Based on comparison with experimental results, Liauw and Kwan (1983) stated that reasonably accurate and conservative results could be achieved by taking $\beta = 1/3$.

Combin 39 is a unidirectional element with nonlinear generalized force-deflection capability that can be used in any analysis. The element has longitudinal capability in 2 or 3 dimensional applications. The element is

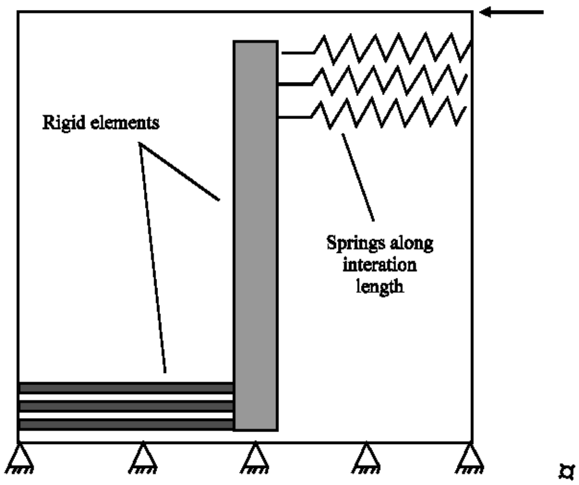

Fig. 7: Modelling of infill wall with nonlinear springs

defined by 2 node points and a generalized force-deflection curve. The force-displacement curve of this element type is represented by straight lines and the coordinates of the line end points (for both tension and compression sides) are given to the software. The points on this curve represent force versus relative translation for structural analyses. Slopes of segments may be either positive or negative, except that the slopes at the origin must be positive. The Combin 39 allows either unloading along the same loading curve or unloading along the line parallel to the slope at the origin of the curve. This second option allows modeling of hysteretic effects.

In order to conduct the nonlinear FEM analysis using material nonlinearity, stress-strain relationships of steel, brick wall and the plaster has to be known. The stress-strain relationship of masonry is nonlinear in compression and negligible in tension; hence, it can not be found in an explicit form (Salah *et al*., 1991). These relationships are obtained through a newly developed procedure. For this purpose, the response of frame systems with and without infill walls under lateral loading (envelope curves) are used. The modelling approach used in this study can be classified as macro-modelling It makes no distinction between the individual units and joints, but considers masonry as a homogeneous, isotropic continuum. This approach may be preferred for the analysis of large masonry structures due to fact that it is difficult to capture all failure mechanisms.

Determination of stress-strain relations and FE analysis: In this part, experimental results of the infilled steel frame test are used. Initially load-deflection results of three tests are used. In these tests, the infill materials are; clay brick infill wall, plastered clay infill wall and finally, AAC infill

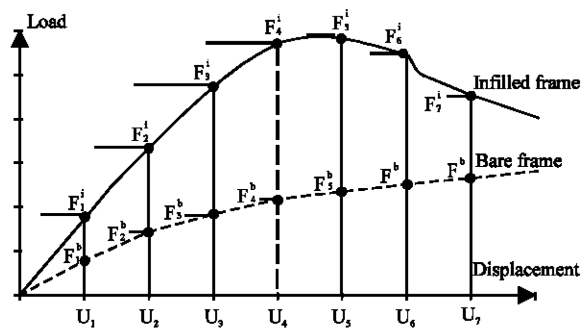

Fig. 8: Representative load-displacement graphs of infilled and bare frames

wall. All three test specimens are fully infilled ($H_m/H_f = 4/4$) and the geometrical properties of the steel frames are constant where length to height value is 1 ($L/H_f = 1$).

In previous studies, several mathematical models are proposed for infill wall panels and they differ from each other (Hakam, 2000). Therefore, in this study, stress-strain relationship of masonry infills are derived from experimental studies and a calibration process is followed. As stated before, only monotonic, load vs. displacement curves (that is envelope curves of the hystersis curves) of tested specimens are considered. Within the steps, adjustment of modulus of elasticity of infill is essential. It is also repeated here that, for calibration procedure only test results of fully infilled frames with $L/H_f = 1$ are used. Other test results are used to compare with analytical results. Referring to the Fig. 8, experimental load vs. displacement curves of bare steel frame and fully infilled frame ($H_m/H_f = 4/4$) are drawn on the same graph where L/H_f is 1. Since the loading applied during testing was displacement controlled, X coordinate (displacement values) of both load-displacement curves coincides and named as U_1, U_2, U_3, ... U_n. Corresponding loads to these displacements are F_1^b, F_2^b, F_3^b.... F_n^b (that is F_j^b (j = 1 to n)) for bare frame and F_1^i, F_2^i, F_3^i.... F_n^i (that is F_j^i (j = 1 to n)) for infilled frame.

Stage 1: In FE model, first, just bare frame is considered. Initially a reasonable value for modulus of elasticity for steel material is attained. A horizontal load (F_1^b) is applied at the top of the frame and corresponding top displacement is noted. If this displacement is higher than the aimed displacement, which is U_1 (real experimental displacement corresponding to loading F_1^b), the modulus of elasticity is decreased. If it is lower than U_1, than the elasticity modulus is increased. This trial and error procedure is repeated until the aimed displacement is obtained. The corresponding dummy elasticity modulus value for step 1 is noted as E_1^b indicating it belongs to bare frame for step 1. This procedure is repeated for all steps and values of E_1^b, E_2^b, E_3^b .... E_n^b are obtained.

Stage 2: For the second stage of the procedure, infilled steel frame, in which infill is modelled with shell elements, is considered (Fig. 5). Again, frame is loaded at the top where the loading value is F_1^i for step1. For elasticity modulus of steel bare frame, E value obtained in stage 1-step1 (E_1^b) is attained. A reasonable initial E value for infill material is assumed and the system is analysed. Calculated top displacement value is compared with U_1, which is real experimental displacement value for lateral load of F_1^i. The E value of infill material is changed so that the corresponding displacement is U_1. Obtained E value for infill is noted as E_1^i indicating that it is dummy Young modulus of infill at step 1. Explained procedure is repeated for all steps and E_1^i, E_2^i, E_3^i ... E_n^i are obtained.

Stage 3: At the last stage, the FE model of the infilled steel frame is remodelled. The shell elements are cleared and a diagonal strut is placed to represent the infill (Fig. 6). Similar procedure is applied for each displacement steps. For displacement step 1, where measured top displacement is U_1, the experimental load F_1^i is applied at the top of the infilled frame model (modelled with diagonal strut). The E value for steel frame material is attained as E_1^b, which is obtained in Stage1-Step1. On the other hand, the E value of infill material, is attained as E_1^i, which is obtained in Stage2-Step1. But in order to run the analysis, another unknown has to be calculated, that is the width of the diagonal strut representing the infill. Again an initial reasonable value for width of the diagonal strut is assumed and analysis is carried out. The top displacement of the model under load of F_1^i is measured from analysis results and compared with real experimental response which is U_1. The width is adjusted to obtain experimental displacement. This procedure is repeated for each displacement steps and corresponding width (w_i) values, w_1, w_2, w_3, w_4, ... w_n are obtained. These widths are observed to be approximately equal to each other (constant) for each displacement steps. The thickness (t) of the diagonal strut is assumed to be equal to width of the masonry infill. Returning to the step1, the axial load in the diagonal strut is calculated from analysis results as N_1 and also for other steps axial compression values are noted as N_1, N_2, N_3..... Nn. The stress values (σ_1, σ_2, σ_3,..._σ_n) in the diagonal strut can be calculated by dividing the axial loads to the are of the strut (equal to the thickness multiplied by width = t * w_i) as;

$$\sigma_i = \frac{N_i}{(t)x(w_i)} \tag{1}$$

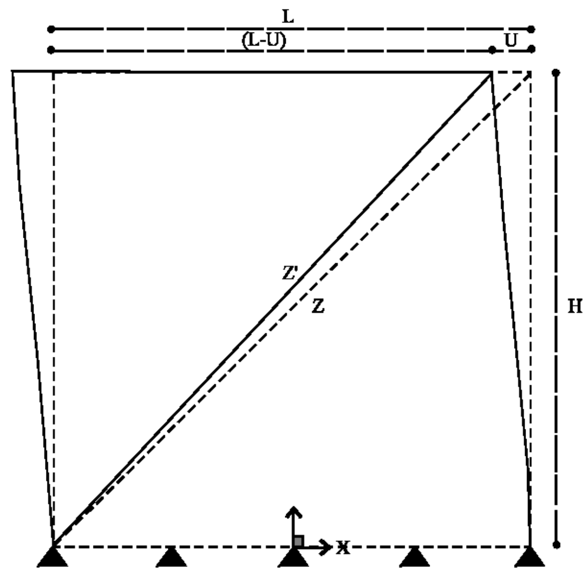

Fig. 9: Diagonal strut model of infill and displacements

Remember that the width values are found to be constant for each step.

Considering the displaced shape of the infilled frame model (Fig. 9), the strain in the strut can be found using the following formulas;

$$Z = \sqrt{(L^2 + H^2)}, \tag{2}$$

$$Z_i' = \sqrt{((L - U_i)^2 + H^2)}, \tag{3}$$

$$\varepsilon_i = \frac{Z - Z'}{Z} \tag{4}$$

Where;

Z : Initial length of diagonal strut
Z_i' : Length of diagonal strut after loading for displacement step1
L : Length of frame
H : Height of frame
ε_i : Strain in the diagonal strut

At this point, stress (σ_i) and strain (ε_i) values are available for infill material. Stress-strain curve of the infilling material can be easily drawn. Above stages and sub-steps are all repeated for all three tests mentioned before. Consequently, three different stress-strain curves are obtained for clay brick infill material, plastered clay brick infill material and AAC infill material. The obtained stress-strain relationships are exhibited in Fig. 10.

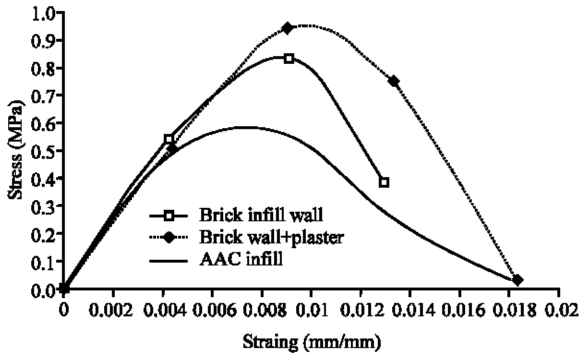

Fig. 10: Stress-strain relationships for brick infill wall with and without plaster, and AAC infill wall systems

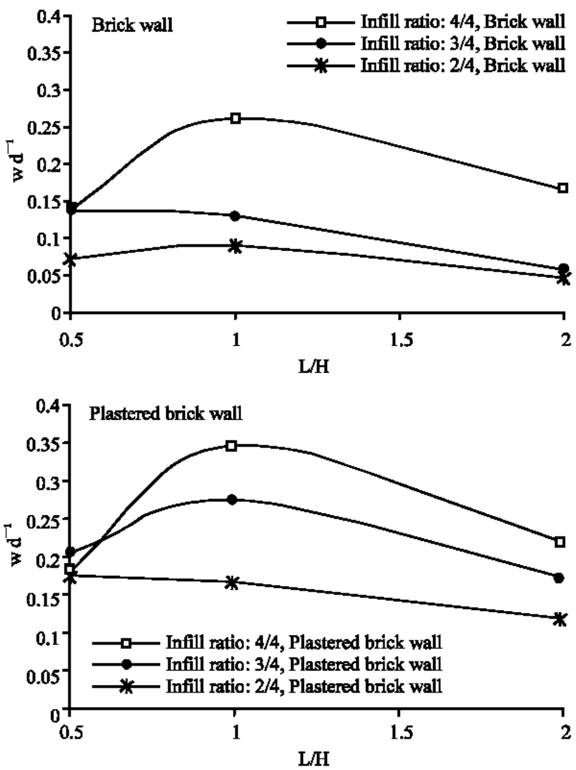

Fig. 11: Effective width of strut vs. L/H ratio

AS states above, the effective width of the diagonal struts are found to be constant for a definite L/H_f value. The way of expressing the effective widths is to divide the computed widths (w_i) to the diagonal strut length (Z) and they are drawn versus L/H_f values in Fig. 11.

Analysis of the model with shell elements: In this part several analysis are carried out to compare experimental and analytical results. The experimental results contains frame test with different L/H_f values which are 1, 2 and 1/2. Also masonry wall proportions (H_m/H_f) are 4/4, 3/4 and 2/4. For infill material three different alternatives are tested (brick infill, plastered brick infill and AAC infill). The FE analyses are carried out to find nonlinear load-displacement relationship of all 24 configurations.

The nonlinear stress-strain relations for infill panels that are obtained from the above procedure are used as input data for ANSYS (Fig. 10) and the model, where infill wall is represented with shell elements, is analyzed and their nonlinear lateral load vs. top displacement curves are obtained. It is not a surprise to find exactly same relation between experimental and analytical results of specimens with $L/H_f = 1$ and $H_m/H_f = 4/4$. But comparison of other test and analytical results may present a tool for evaluating validity of the proposed material model. These curves will be presented with other analytical results in the following part.

Analysis of the diagonal strut model: In this model, infill panel is represented with a diagonal strut as explained previously. The stress-strain relations of infill panels (obtained previously shown in Fig. 10) are used for the struts. The width of the struts are taken from w_i values calculated in stage3. Nonlinear analysis results (load vs. displacement curves) are compared with experimental curves. Again these curves will be presented with other analytical results in the following part.

Analysis of the model with nonlinear springs: In this part, the masonry infill is modelled with nonlinear springs COMBIN39, elements. The element has longitudinal capability in one, two, or three dimensional applications. The longitudinal option is a uniaxial tension-compression element with up to three degrees of freedom at each node: translations in the nodal x, y, and z directions. No bending or torsion is considered. Element is defined by two node points and a generalized force-deflection curve. The points on this curve (D1, F1, etc.) represent force versus relative translation for structural analyses. The slopes of force-deflection curve segments may be either positive or negative (Fig. 12).

Three springs are connected to the upper corner (loaded corner) of the frame and they are connected to a rigid bar in the middle of the frame as shown in Fig. 7. The rigid member is also connected to the opposite side of the frame close to the bottom corner (opposite to the loaded corner) in order to transfer the load to the opposite corner of the frame. These springs are placed through the effective infill contact length. For this length, an approximate value given by Liauw and Kwan (1983) which is 1/3 of the wall height is chosen.

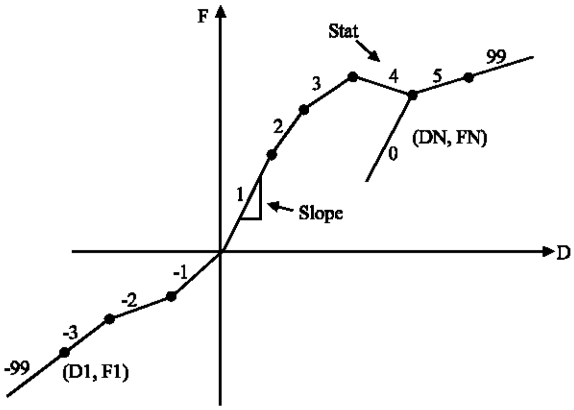

Fig. 12: COMBIN39 nonlinear spring

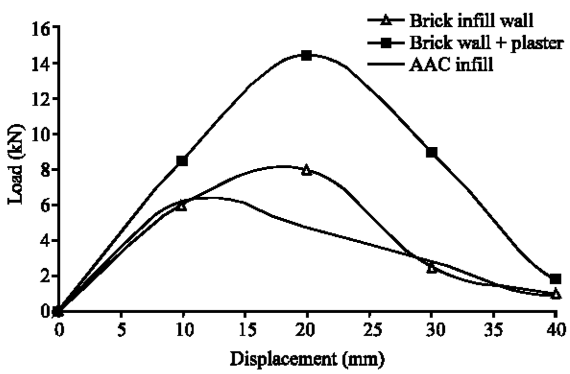

Fig. 13: Force-displacement curves for springs

In order to run the analysis, nonlinear force-displacement curve of the spring element is required. For this purpose, again, a trial and error procedure is adopted. Only 3 specimens' load-displacement envelope curves are used which are; frame with brick infill, frame with plastered infill and frame with AAC infill where $L/H_f = 1$ and infill ratio is $H_m/H_f = 4/4$. Determination of force vs. displacement curves of spring is different from previous trial and procedure. Force vs. displacement curves of springs are represented with several points and they are adjusted to get an similar load vs. displacement curve to experimental one. Finally, three force vs. displacement curves are obtained representing brick infill, plastered infill and AAC infill. The obtained force-displacement curves for springs are given in Fig. 13.

The number of nonlinear springs can be increased or decreased but the analysis time will increase with an increase in number of springs.

RESULTS

In Fig. 14, for AAC infilled frames (L/H = 1 and for infill ratios of 4/4, 3/4 and 2/4), the analysis results of the

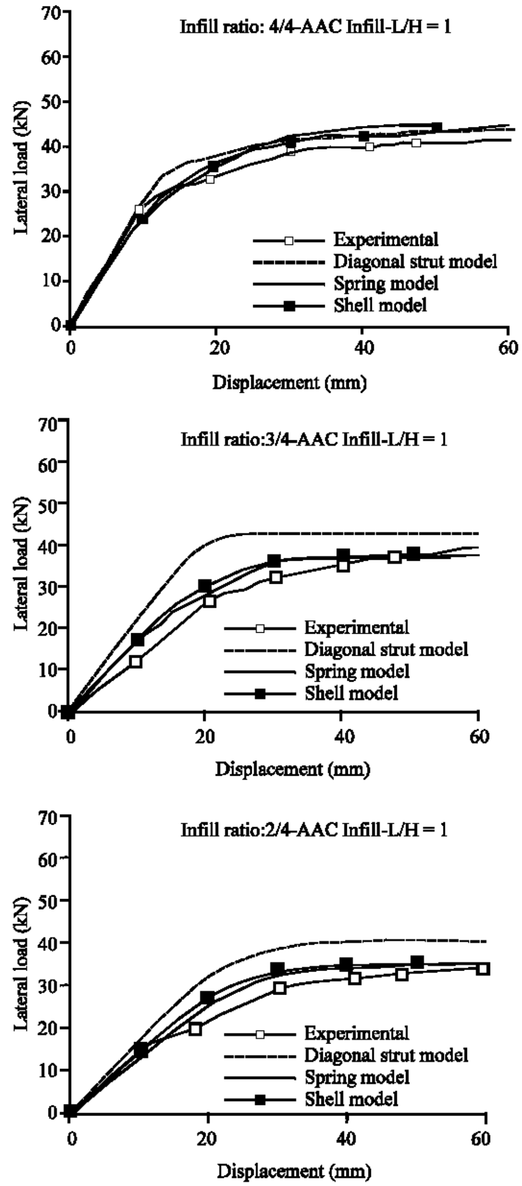

Fig. 14: Comparison of FEM analysis and experimental envelope curves for AAC infilled wall

model with shell elements, diagonal strut model and spring model are given and compared with the experimentally obtained ones. For these three models with different approaches, in Fig. 15-17, load-displacement curves are presented along with the experimental results. The distinct parameters of the specimens are; infill wall material (brick wall with and without plaster, AAC infill), ratio of infill (4/4, 3/4, 2/4) and L/H ratio (1, 1/2, 2).

It is worth to say here that, the experimental and analytical results of fully infilled frames with $L/H_f = 1$ are coincide with each other, because the E values are

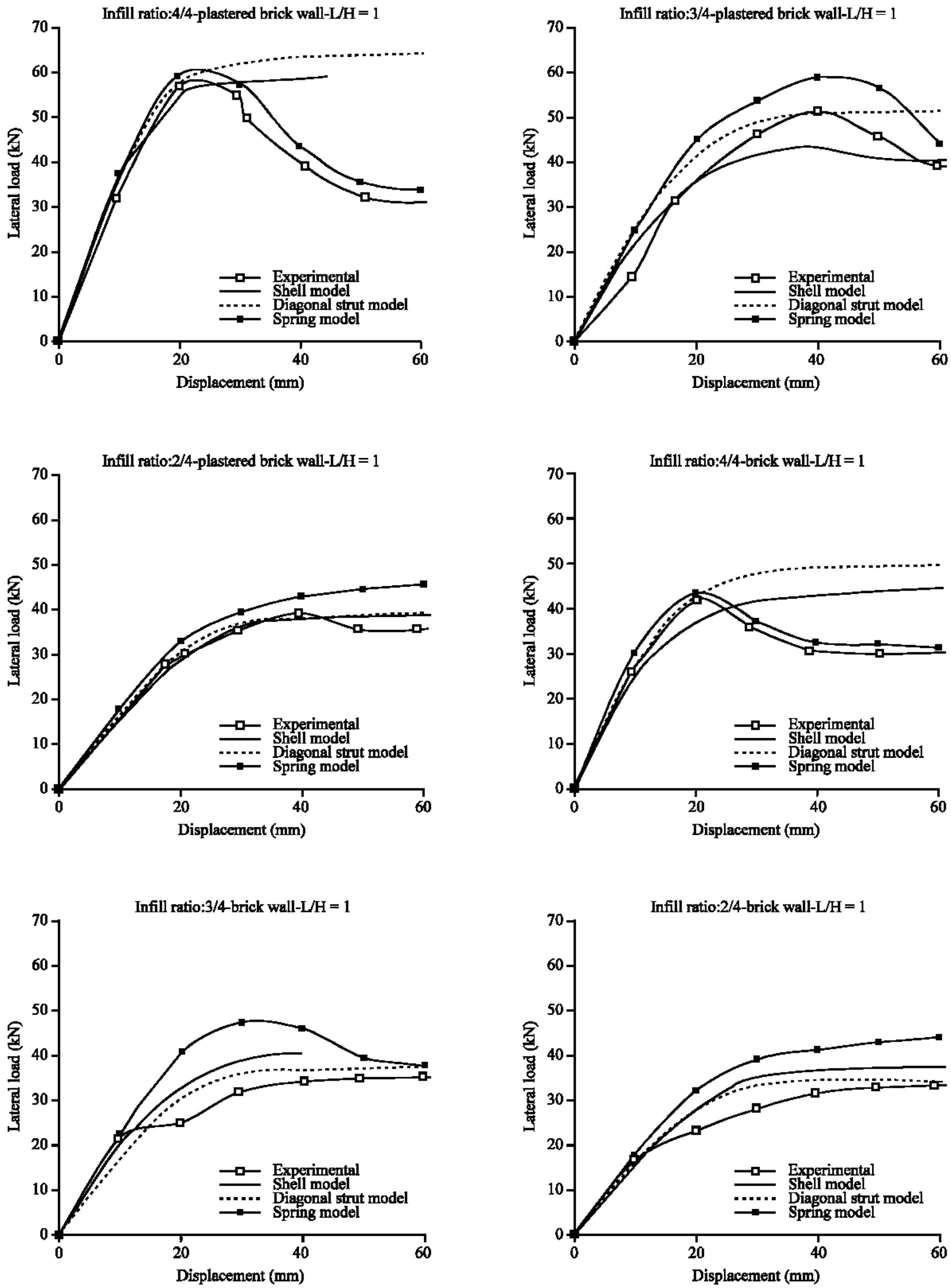

Fig. 15: Comparison of FEM analysis and experimental envelope curves for plastered and non-plastered brick infill walls (L/H = 1)

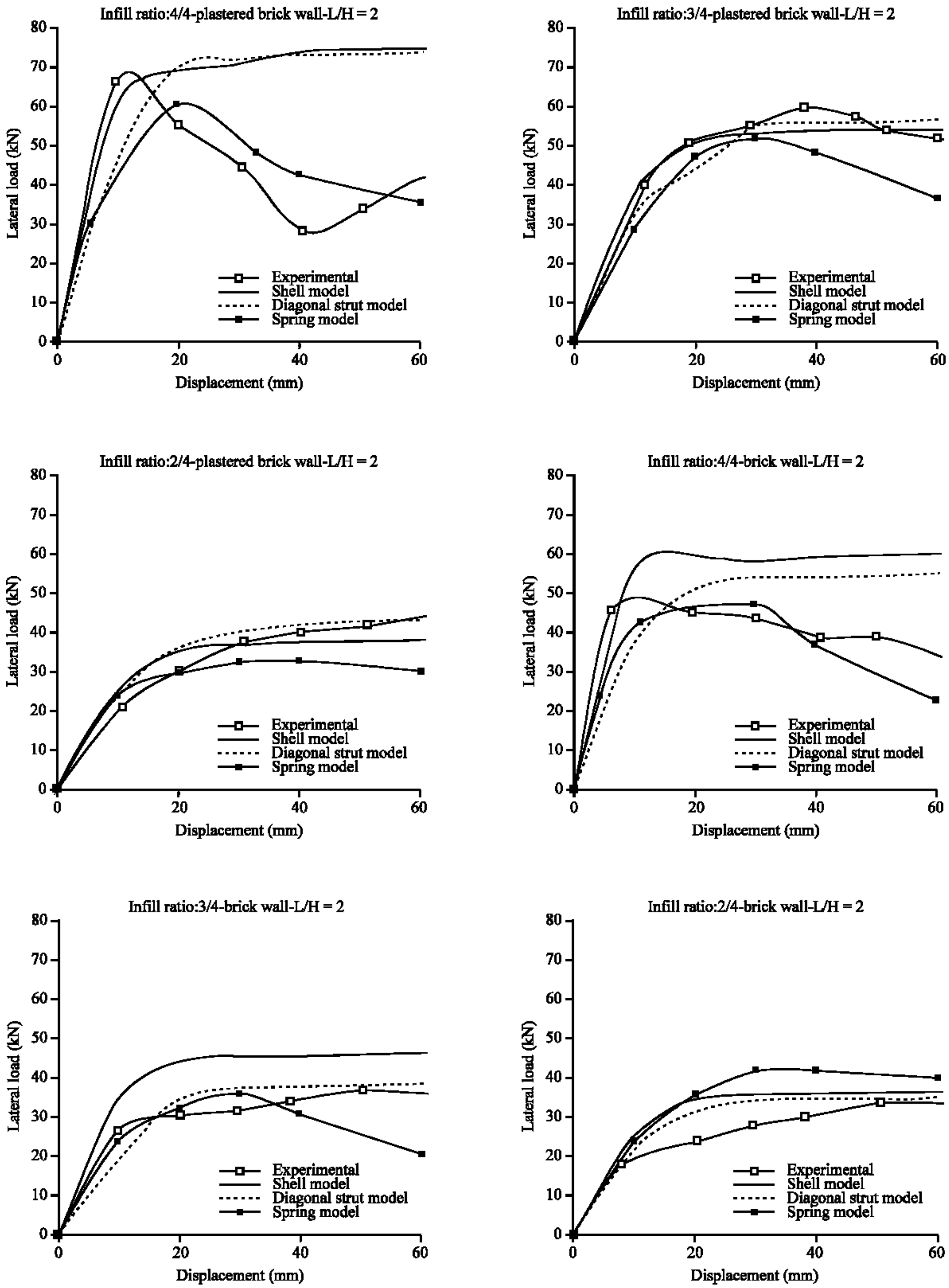

Fig. 16: Comparison of FEM analysis and experimental envelope curves for plastered and non-plastered brick infill walls (L/H = 2)

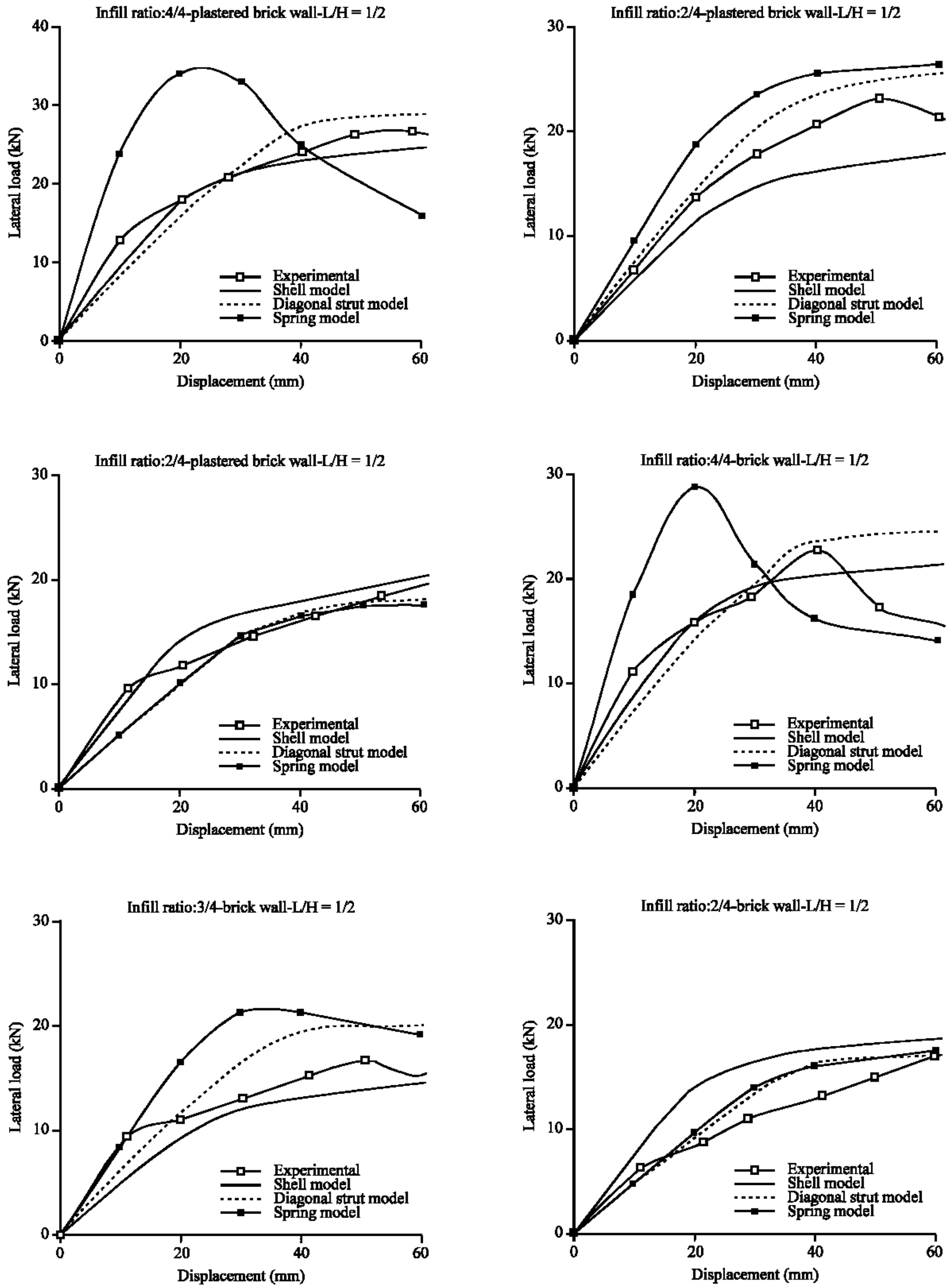

Fig. 17: Comparison of FEM analysis and experimental envelope curves for plastered and non-plastered brick infill walls (L/H = 1/2)

modified to capture the same load vs. displacement curves. On the other hand, comparison of other specimens test and analytical results can supply information to readers to get an idea whether the proposed model and method is valid or not.

DISCUSSION

The contribution of infill panels to load carrying capacity and lateral rigidity of frame systems is significant. Taking this additional capacity into account is not only necessary to obtain realistic designs but also beneficial resulting in more economical designs. However, for this consideration, a reliable model is required to be used in structural analysis. In this study, new approches to modelling of infill walls are developed to consider the contribution of infill panels.

In earthquake analysis, nonlinear analyses are superior to linear elastic analysis. But nonlinear material model of used wall panels can show differences in the literature. In this study this material relations (stress-strain) are determined with a trail and error procedure. Also change of width of diagonal strut with L/H ratio is determined and a new modelling approach with springs is presented.

The most important problem in studies of infill walls are; influence of workmanship and local materials. It is obvious that the results presented in this paper may change in other parts of the world. To take into account all these subjective parameters in this study is impossible.

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