Design assumptions and their impact in strengthening of RC frames with RC infills

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ABSTRACT: The behaviour of reinforced concrete (RC) infilled frames depends strongly on the way the infill is connected to the surrounding frame. Modeling the infilled frame involves a number of parameters, the value of which may alter significantly the results, both in terms of demand and of capacity. This work attempts to point out the importance of the various design parameters and their impact on design. Code provisions of FEMA and ASCE are discussed and evaluated by the results of tests on 1/3-scale RC infilled frames. A simple engineering frame model and practical recommendations for the design of RC infills are offered.

1 INTRODUCTION

Reinforced concrete (RC) buildings designed according to the older generation of codes are generally deficient in seismic resistance and vulnerable to a future earthquake. These buildings are often irregular, include soft stories, strong beam-weak column connections, short (captive) columns, and have inadequate seismic detailing. Shear strength of the bearing elements, especially of columns, is considerably lower than their respective flexural capacity due to the low amount of stirrups present. The lack of capacity design concepts, in combination with inadequate design and the low strength of materials used, make older buildings seismically unsafe. They inherently possess low energy dissipation capacity, and often also low strength and stiffness characteristics. The strengthening of similar structures by including RC infills in the existing substandard RC frames results in considerable increase of strength and stiffness and reduction of the displacements. Hence, seismic risk because of deficient design is reduced.

In modern codes no detailed provisions are generally available regarding the design of RC infilled frames (i.e. RC frames strengthened with RC infill walls). However, how the infill is modelled strongly influences the analytical results from the design model. Further on, the actual behaviour of RC infilled frames when subjected to racking (horizontal) loads strongly depends on the detailing of the infill, e.g. infill geometry, how the infill is connected to the existing frame.

In this work it is discussed how the prevalent design procedure for the modelling of RC infilled frames is dealt with in ASCE 41-06 (2006) and FEMA 306 (1998). Moreover, the calculation of the strength of RC infilled frames for all possible modes of failure, is discussed. Finally, the code provisions are evaluated by their capacity to describe the experimental results of 1/3-scale tests on RC frames strengthened by RC walls, with different ways of connection between the wall and the infill. As a result of this work, practical recommendations for the design of RC infills are proposed.

2 BEHAVIOUR OF RC INFILLED FRAMES SUBJECTED TO RACKING LOAD

2.1 General

Estimation of the stiffness and the resistance of RC infilled frames are essential for the accuracy of modeling the strengthened structure. Both the stiffness and the resistance depend on the way the infill is connected to the frame. The deterioration of this connection with the progress of cyclic loading affects the stiffness, the ductility, the way the forces are transmitted between the frame and the wall, and finally the resistance of the RC infilled frame, i.e. the load at which failure occurs.

When RC infilled frames are subjected to low horizontal excitation, the RC frame and infill act in a fully composite manner and the infilled frame behaves as a structural wall with boundary elements. When lateral loading increases, the frame attempts to deform in flexure, whereas the infill deforms in shear (Figure 1). As a consequence, the infill tends to separate from the frame in the corners of the diagonal that is subjected to tension (Paulay et al, 1992). At further increase of loading, relative slippage occurs along the construction joints, mainly the horizontal ones. The onset of relative slippage leads to deterioration of the RC infilled frame (Moretti et al, 2014, and Synge, 1980).

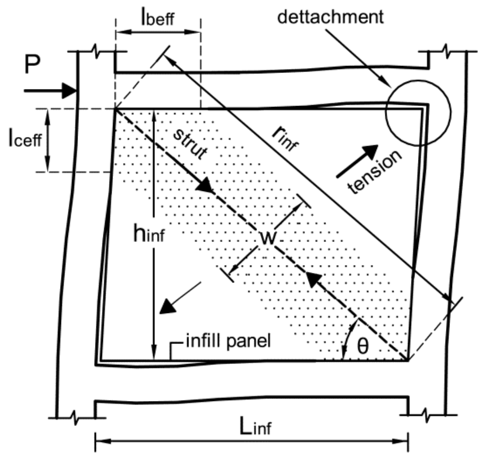

Figure 1. Characteristics of RC infilled frames subjected to racking load P.

2.2 Modelling of infill walls through diagonal struts

The infills are usually modelled through one or more diagonal concrete struts, activated only when subjected to compression. In the diagonal strut model the thickness, t, and the material properties of the strut (i.e. modulus of elasticity, E_m) correspond to those of the infill. The effective width, w, of the strut is calculated according to different analytical concepts and may lead to significant divergence of results, regarding the shear resistance and also the stiffness (Moretti et al, 2014). The approach of various codes regarding infilled frames differs considerably. EN1998-3 (2005) does not include specific provisions for the design of infilled frames. The Greek code (KAN.EPE, 2012) assumes an effective strut width equal to 0.15 of the infill's length of the diagonal, r_{inf}. FEMA 306 (1998) and ASCE 41-06 (2006) standards include detailed provisions for the estimation of the strength and the failure mode of infilled frames, applicable to both masonry and RC infills, and therefore they will be used in this work.

According to FEMA 306 (1998) and ASCE 41-06 (2006) the width of the strut, w, and the strut's contact length with the column, l_{ceff}, and the beam, l_{beff} (Figure 1), are calculated by equations (1) to (4):

$$w = 0.175(\lambda \cdot h_{col})^{-0.4} r_{\inf} \tag{1}$$

$$\lambda = \sqrt[4]{\frac{E_m \cdot t_{\inf} \cdot \sin 2\theta}{4E_f \cdot I_{col} \cdot h_{\inf}}} \tag{2}$$

$$l_{ceff} = w / \cos\theta_c, \qquad \text{where} \quad \tan\theta_c = (h_{\inf} - w/\cos\theta_c)/L_{\inf} \tag{3}$$

$$l_{beff} = w / \sin\theta_b, \qquad \text{where} \quad \tan\theta_b = h_{\inf} /(L_{\inf} - w/\sin\theta_b) \tag{4}$$

where E_m, $t_{\inf}$, $h_{\inf}$, $L_{\inf}$ and $r_{\inf}$ are the infill's Young's modulus of elasticity, thickness, height, length, and diagonal's length, respectively, E_f, I_{col} and h_{col} are the Young's modulus of elasticity, moment of inertia and height of the columns, while θ is the angle whose tangent is the infill's height-to-length aspect ratio, $\tan\theta = h_{\inf} / L_{\inf}$ (Figure 1).

2.3 Potential modes of failure and the circumstances under which they may occur

In case of infilled frames the possible modes of failure, according to FEMA 306 Guidelines (1998), are listed below. The conditions required for each mode of failure to occur, sustained by the observations and the results from an experimental program (Perdikaris et al, 2012, and Moretti et al, 2014) are pinpointed.

2.3.1 Failure in compression of the infill wall

The maximum horizontal load that can be undertaken by a RC infilled frame is supposed to be equal to the horizontal constituent of the resistance of the diagonal concrete infill strut, with concrete compressive strength f_c: $V_c = w \cdot t_{\inf} \cdot f_c \cdot \cos\theta$. This specific mode of failure in RC infilled frames may occur only when the frame elements are reinforced according to modern design concepts, and the columns (boundary elements) are considerably stronger than the infill. From test results (Moretti et al, 2014) it has been shown that: a) The concrete strut is more activated in case of strong boundary elements and strong connection between the frame and the RC wall (Oesterle et al, 1976 and 1979, b) The average strain measured along the diagonal under compression along the entire frame is higher than the concrete strain of the RC wall along the same diagonal. This means that the infill along the diagonal in compression is not actually stressed so much as it would be expected according to the concept of the strut model.

2.3.2 Failure in tension of the infill wall

It is supposed to occur along the infill diagonal subjected to tension. It is noted that after the advent of separation between the infill and the frame at the end parts of the diagonal in tension, this mode of failure is not likely to occur in a RC infill.

2.3.3 Flexural failure of the infilled frame

The resistance in bending moment of the RC infilled frame is calculated at the base cross-section, assuming linear strain distribution (EN1992-1-1, 2004). This assumption is not accurate in general (Moretti et al, 2014). The contribution of dowels, present along the interface between wall and frame, should not been taken into account, unless the embedment length, both in the infill and in the frame members, is at least equal to the anchorage length, thus permitting the participation of dowels in undertaking the bending moment.

2.3.4 Shear sliding failure

The resistance against shear sliding along the horizontal interfaces between the infill and the frame consists mainly in friction forces along the part of the interface under compression, as well as in dowel forces, and may be calculated according to appropriate code provisions. The basic problem is that the knowledge of the relative slip at the interfaces is difficult to calculate. It depends on a number of inter-related parameters and may only be estimated (with doubtful accuracy) by sophisticated finite models which reproduce the behaviour along the frame/infill interfaces. The maximum resistance of each load carrying mechanism along the interface is activated at different values of relative slip. A safe lower limit would be to calculate only the contribution of the dowels, but reduced due to cyclic loading. It is noted that the horizontal force acting on a RC infilled frame is primarily supposed to be carried by the diagonal concrete strut. So, only a part of the acting force is supposed to be transferred along the horizontal interfaces. The external force acting along the interface increases as the value of the relative slip increases.

2.3.5 Failure of frame members

According to FEMA 306 (1998) the strut activated from the infill may cause premature failure to the frame members converging to the joint, because the column and/or the beam at length equal to l_{ceff} and/or l_{beff}, respectively, may behave as "captive" elements. In order to avoid shear failure, the particular elements should be capable of sustaining shear force at least equal to $(M_R^+ + M_R^-)/l_{eff}$, where M_R is the flexural resistance of the members. The demand in shear calculated in this way is high, and it is difficult for substandard structures to be reinforced so as to be able to sustain a similar shear force. However, no shear failure occurred in the frame elements in the tests which are briefly described in the following (Moretti et al, 2014), although shear failure should have occurred according to FEMA 306 (1998).

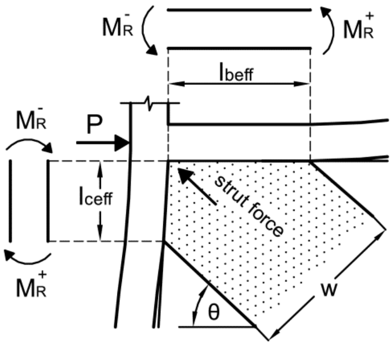

Figure 2. Potential bending moments acting on the frame members incited by the infill strut.

2.3.6 Failure of the frame joints

Frame joints may fail either in compression, or in tension. FEMA 306 offers a procedure for calculating the principal stresses in the joint so as to assess if joint failure should be expected. Particularly vulnerable to failure in tension are the joints of substandard frames, while joints of strengthened columns are liable to fail in compression (Moretti et al, 2014).

2.4 *Interface between RC wall and RC frame*

The best method for connecting the infill to the frame has proved to be by adhesive dowels (Altin et al, 1992). The presence of dowels along the entire perimeter of the infill, compared to dowels only along the horizontal interfaces, results in increased overall stiffness and response degradation. The surface of the RC frame which is in contact with the RC infill may be artificially roughened, or not roughened. Artificial roughening is supposed to lead to increased activation of friction forces along the interfaces, but also to more abrupt degradation of shear resistance along the interface. At high levels of horizontal load, the roughening of interfaces do not appear to reduce relative slippage (Moretti et al, 2014).

3 ASCE/SEI (2006) CODE PROVISIONS APPLIED ON EXPERIMENTAL RESULTS

Basic conclusions from the application of ASCE/SEI (2006) provisions to describe the observed behaviour of 1/3-scale specimens tested in the Laboratory of Concrete Technology and Reinforced Concrete Structures of the University of Thessaly will be briefly discussed in the following. Two infill aspect ratios $L_{\text{inf}} / h_{\text{inf}}$ were tested. In the test specimens the RC infill was either not connected to the frame, or connected through dowels either along the entire perimeter, or only along the horizontal interfaces (Figure 3). Normal dowels had embedment length 50 mm (8 bar diameters) in the frame members and 100 mm in the infill, and long dowele (in A7, B1, and B2) had embedment length equal to 60 mm in the frame, 120 mm in the foundation and 200 mm in the infill. Roughening of the interfaces took place only in A6 and A7 (in which the columns were jacketed). The frame members were substandard, designed according to old Greek codes. More detailed information on the tests may be found elsewhere (Perdikaris et al, 2012, and Moretti et al, 2014).

Table 1 reports the ratios of the maximum experimental horizontal load, P_{max}, to the values of horizontal force that would cause (according to FEMA 306) compressive failure of the

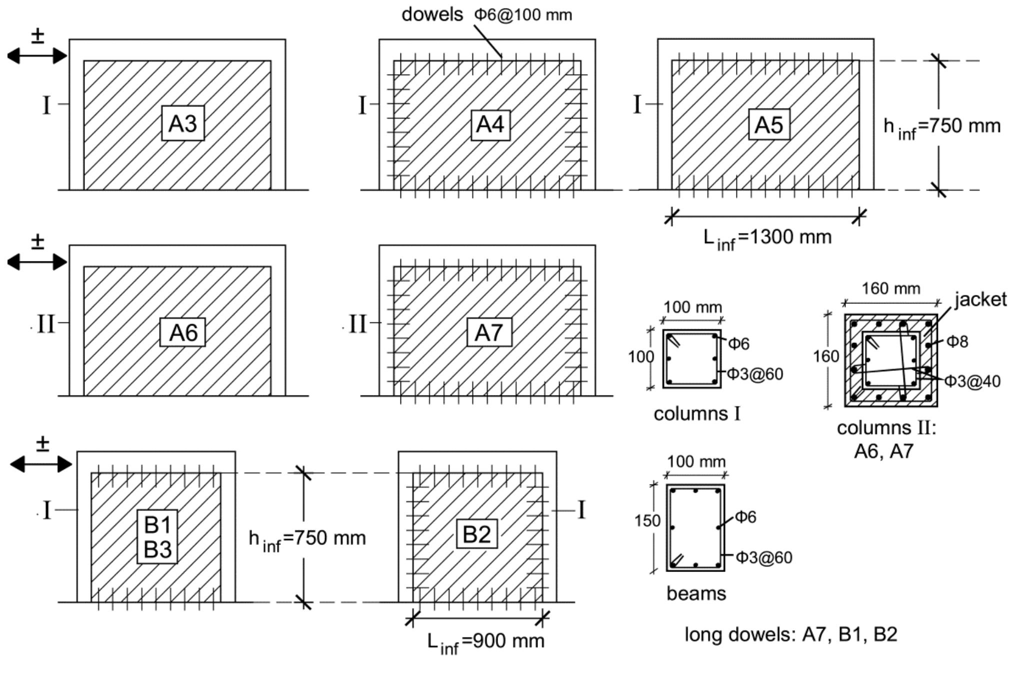

Figure 3. Characteristics of specimens tested in UTH.

Table 1. Ratios of experimental to analytical values of horizontal displacement and shear resistance.

specimen	L_{inf}/h_{inf}	$\delta_{exp}/\delta_{mod}$ (P_{max})	$\delta_{exp}/\delta_{mod}$ ($0.5P_{max}$)	P_{max}/V_c	P_{max}/V_{DT}	$P_{max}/V(M_R)$
A3	1.73	0.68	0.74	0.55	0.42	0.82
A4	1.73	0.48	0.38	0.85	0.65	1.27
A5	1.73	0.76	0.77	0.85	0.64	1.23
A6	1.73	1.06	0.19	1.46	1.25	0.40
A7	1.73	0.69	0.26	1.80	1.60	0.53
B1	1.20	0.97	0.34	1.04	0.67	1.36
B2	1.20	0.39	0.33	1.27	0.79	1.51
B3	1.20	1.04	0.55	0.87	0.56	1.14

strut (V_c), diagonal tension failure of the infill (V_{DT}) and flexural failure at the base of the RC infilled frame ($V(M_R)$). According to the code predictions, the infills of specimens A6 and A7 with columns strengthened with jackets, were supposed to fail in compression and tension.

Furthermore, compressive failure of the strut was supposed to occur in specimens B1 and B2, with long dowels, while flexural failure at the base cross-section was expected in specimens A4, A5 and B1 to B3 (with lower aspect ratio L_{inf}/h_{inf}). At the tests, cracking of the infill was observed only when long dowels were present (specimens A7, B1, and B2), but these cracks did not lead to failure. In general, cracks first appeared in the frame joint, and failure finally occurred along the infill/frame interface, with shearing of the dowels, in most cases.

3.1 Simple engineering model for the RC infilled specimens

The infilled frames may be modelled by substituting the infill with a compression strut (either single or multiple struts, Figure 4), connected with the frame by pins, with width w calculated according to (1) and (2), and properties those of the infill. For loads up to $0.50P_{max}$ unreduced stiffness properties are assumed. For higher loads up to P_{max} the stiffness of the frame members is assumed to be 50% of the elastic value, and the width of the strut equal to 50% of the value calculated according to (1) and (2), the latter based on findings of Paulay et al (1992). The values δ_{mod} (P_{max}) of the horizontal displacement of the frames resulting from the solution of the frame models for applied horizontal load equal to the observed P_{max} (with 50% member stiffness) and the displacements for $0.50P_{max}$ (with uncracked stiffness), δ_{mod} ($0.5P_{max}$), are shown in Table 1 as a ratio of the respective horizontal displacement δ_{exp} from the test. It may be observed that the frame model overestimates in general the stiffness of the infilled frames (because it estimates lower displacements than the ones actually observed) especially for horizontal load equal to $0.50P_{max}$. In case of load P_{max} the model underestimates the horizontal displacements more in the case of stiffer specimens, i.e. with dowels along the entire perimeter (A4, A7, and B2). Best predictions are obtained when the infill was modelled though a single strut, as compared to a triple strut with the widths shown in Figure 4 (Fotakopoulos et al, 2013).

3.2 Verification of the frame joints

The joints of the specimens were checked according to the FEMA 306 provisions for the forces that result from the solution of the equivalent frame presented in 3.1 for horizontal load equal to the maximum observed, P_{max}. It is assumed that prior to detachment between infill and frame the forces acting at the joint are those of Figure 5(b), while after detachment occurs the constituents of the strut are transferred to the beam, thus altering the state of stresses in the joint. For specimen A7 the forces at the joint from the solution of simple- and triple-strut frame model are depicted in Figure 6. When the provisions proposed in FEMA 306 are applied to specimen A7 it results that: a) for the simple strut model the joint of A7 is liable to fail in compression prior to detachment (principal compressive strength $\sigma_c = -20.7MPa > 0.5 f_c$, principal tensile stress $\sigma_t < 3.5 \cdot 0.083\sqrt{f_c}$) , and b) for the triple strut compressive failure of the joint is supposed to occur when the forces of only the central strut are taken into account: $\sigma_c = -16.6MPa > 0.5 f_c$.

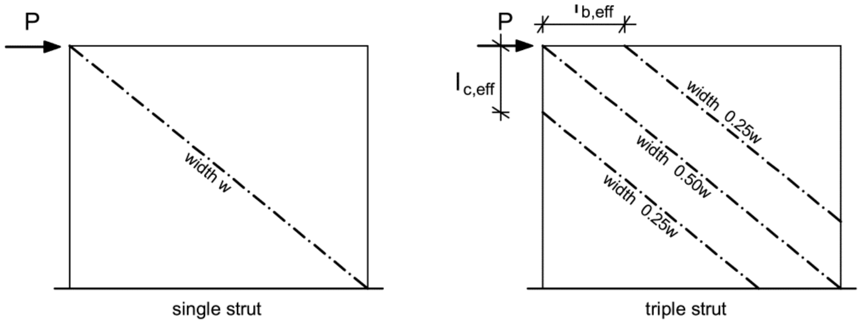

Figure 4. Strut width, w, for single and triple strut models.

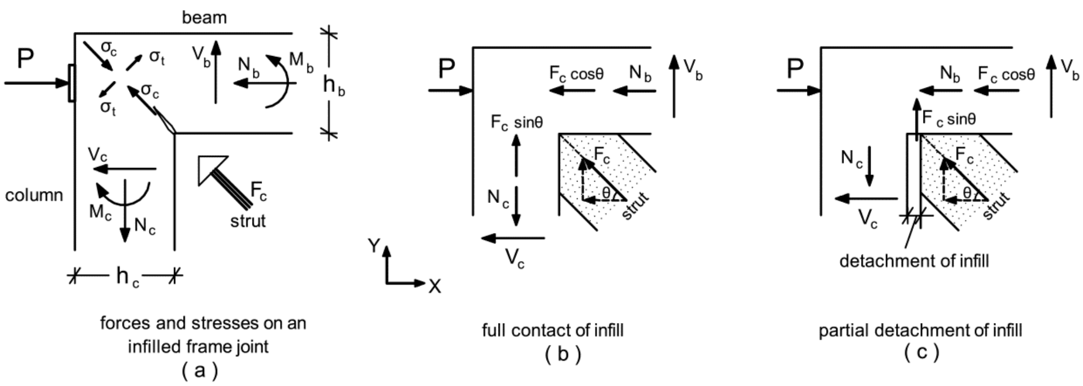

Figure 5. Forces and stresses acting on a joint of a frame strengthened with an infill.

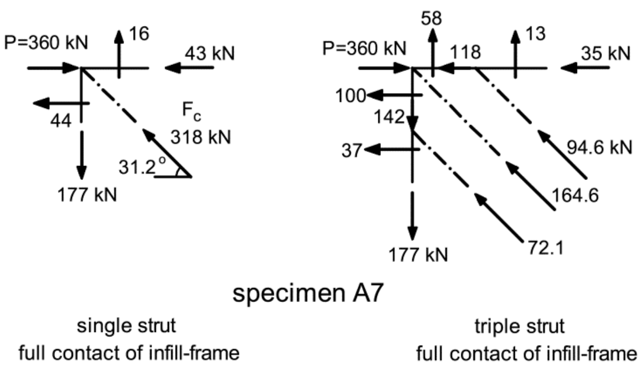

Figure 6. Forces from the solution of the model frame for specimen A7 for load P_{max}=360 kN.

4 RECOMMENDATIONS - CONCLUSIONS

The basic conclusions of this work are summarized as follows: The connection of the infill to the surrounding frame is very important, because failure is generally caused after the initiation of relative slippage between the infill/frame interfaces. It is argued that the calculation of the resistance against shear sliding is not so important per se: the forces acting along the interfaces are difficult to calculate because they depend on many parameters. Furthermore, the interaction between infill and frame introduces forces in the frame joints, which differ after the advent of detachment between infill and frame. Modelling the interaction of the infill and the frame is also of importance because the results may vary considerably with the choice of the different parameters for the model. A simple engineering model, calibrated on experimental results, is proposed.

Finally, the potential failure modes for infilled frames proposed by FEMA 306 (1998), initially formulated for masonry infilled frames, are discussed. It is noted that the stiffness and the strength of masonry infills are considerably inferior to those of RC infills. This fact has the following effects: a) The RC infill is rarely damaged, compared to a masonry infill with the same geometrical characteristics, b) The RC frame suffers more damage in case of RC infill walls than in the case of masonry walls, and c) In RC infills the type of connection between the infill and frame may significantly affect the behavior of the infilled frame.

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