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Seismic design and analysis of masonry-infilled frames

V.K.R. Kodur, M.A. Erki, and J.H.P. Quenneville

Abstract: A simple analytical procedure, which can be used by practicing engineers, for the seismic design of masonry-infilled frames is presented. The analysis procedure, based on the experimental and analytical studies reported in the literature, accounts for the effect of infills in all three stages, namely, in computing seismic loading, in predicting response of the infilled frame, and in determining the strength of the infilled frame. Seismic loading is computed using the dynamic properties of the structure rather than arbitrary empirical relationships as recommended in design codes. Recommendations regarding the choice of infilled frame idealization, structural damping ratio, earthquake design spectrum, structural irregularity, and computational aids are made. Practical guidelines, which can be implemented during the construction phase and which have beneficial effects on the behaviour of infilled frames, are provided. Application of the proposed analytical procedure in a design situation is demonstrated through a numerical example, and it is shown that infills can be accounted for in the seismic design of frames during the normal course of design.

Key words: masonry, infilled panels, frame behaviour, seismic design.

Résumé : Une méthode analytique simple, qui peut être utilisée par les ingénieurs dans le calcul parasismique des ossatures avec remplissage de maçonnerie, est présentée. Cette méthode, basée sur les études analytiques et expérimentales répertoriées dans la littérature scientifique, tient compte de l'effet du remplissage à trois étapes, soit lors du calcul de la charge sismique, de la prévision de la réponse de l'ossature avec remplissage et de l'établissement de sa résistance. La charge sismique est calculée à l'aide des propriétés dynamiques de la structure plutôt qu'avec des relations empiriques arbitraires comme le stipulent les codes de conception. Des recommandations concernant le choix d'idéalisation de l'ossature avec remplissage, de rapport d'amortissement, de spectre de calcul parasismique, d'irrégularité structurale et d'outils de calcul sont effectuées. Des lignes directrices pratiques, qui peuvent être mises en oeuvre durant la phase de construction et qui ont des effets bénéfiques sur le comportement des ossatures avec remplissage, sont également présentées. L'application de la méthode analytique proposée à la phase de conception est illustrée à l'aide d'un exemple numérique qui démontre que le remplissage peut être pris en considération dans le calcul parasismique des ossatures durant le processus de conception.

Mots clés : maçonnerie, panneaux avec remplissage, comportement d'ossature, calcul parasismique.
[Traduit par la rédaction]

Introduction

Concrete and steel frames, which find wide applications in multistorey buildings, are often infilled with brick or concrete-block masonry for functional reasons. When the infill panel is connected to the frame, the total system acts as a single unit; whereas in the case of a panel separated from the frame, by

means of adequate joints, the frame system can deform freely during an earthquake. These infill walls, though constructed as secondary structural elements, behave as a constituent part of the structural system and determine the overall behaviour of the structure, especially when it is subjected to seismic loads. However, designers tend to treat these infill walls as "nonstructural" and treat the frames as conventional frames, a practice that is far from representing the true behaviour.

Infilled frames, like any other structures, should be designed to withstand lateral forces that can result from seismic ground motion. The accuracy of the predicted forces induced by an earthquake depends on the accuracy of the calculated dynamic characteristics of the structure, namely natural frequencies, free vibrational modes, and damping. The dynamic properties are significantly influenced by the presence of the infill. Empirical relationships, as proposed in design codes of practice, do not properly account for the effect of the infill. Furthermore, errors greater than $\pm 50\%$ were observed (Ellis 1980) when the natural frequencies, computed using empirical

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formulas, were compared with measured natural frequencies. Hence, the dynamic characteristics of an infilled frame should be determined by accounting for the effect of infill.

The neglect of infills in seismic design can be attributed to the common misconception that masonry infill in frames can only increase the overall lateral load capacity, and, therefore, must always be beneficial to seismic performance. However, a number of structural damages, as recorded in some of the recent earthquakes (Minami 1987; Mitchell 1987; Mitchell et al. 1986; Stratta 1987), were traced to modifications of the structural frame due to the presence of infilled walls. Hence, there is an increasing recognition (Chavez 1992; Minami 1987; Villablanca et al. 1990) among structural engineers that the infilled walls affect the characteristics of the building under the effect of dynamic loads, specifically wind and earthquake loads, and should be taken into consideration in design and analysis. It is now possible to account for the effect of infills, because of the improved analytical and experimental techniques in recent years.

A review of the literature on the behaviour of infilled frames (Kodur et al. 1994) indicated that the addition of infills may cause significant changes in the dynamic characteristics of buildings and influence their behaviour during earthquakes. According to Bertero and Brokken (1983), an infill that is properly designed and connected to the frame offers conceptual and practical advantages, particularly if the basic structural system is a moment resisting frame. Also, seismic resistant design should be based on the principle of avoiding unnecessary masses and using necessary masses structurally to resist seismic effects. Thus, when walls and partitions are needed, attempts should be made to use masonry or concrete walls and partitions as structural elements.

Unfortunately, the lack of a simple, practical method for the analysis of infilled frames has led, in some cases, to the design of buildings without accounting for the effect of the infills. The literature review on infilled frames revealed the need for developing guidelines for the design and analysis of infilled frames. An analysis technique for the seismic design of infilled frames, which can be used by practising engineers, is presented in this paper. The steps associated with the analysis are listed, and special factors to be considered in the design phase and construction phase are described in detail.

Frame – infill interaction

Flexible frames on their own offer little resistance to lateral forces, resulting often in large deflections and rotations at the joints. Similarly, panels or walls subjected to lateral loads fail mainly in shear at relatively low loads and at small displacements. When the frames and panels act together, the combined action of the composite system differs significantly from that of frame or wall alone. Provided that the infilled frame is properly designed and detailed, the infilled frame may demonstrate enhanced lateral load resistance, improved lateral stability, and smaller deformations. This increased resistance of the infilled frame can be attributed to the development of high axial forces and bending moments in the frame, and to the confinement of the infill. Infills develop high diagonal forces, but lower shear stresses.

The influence of well-designed infill walls on the main mechanical characteristics of a reinforced concrete (RC) brick-

Table 1. Comparison of infilled frame behaviour with reinforced concrete frame behaviour.

No.	Factor	RC frame	RC frame with brick infill
1	Load capacity	1	≈ 2
2	Initial stiffness	1	≈ 5
3	Stiffness at service load	1	≈ 2.7
4	Cumulative ductility	≈ 3.3	1
5	Energy dissipation capacity	1	≈ 1.5
6	Lateral strength	1	≈ 6
7	Natural period	1	< 6
8	Earthquake (inertial) forces	1	> 1
9	Energy dissipation	See note*	See note†
10	Resistance to incremental collapse	1	> 1

*Energy dissipation through large inelastic rotations at hinge regions.

†Energy dissipation through hysteretic behaviour (friction across panel cracks).

infilled frame is compared with that of a bare RC frame in Table 1. This comparison, using performance factors, is based on the results from previous investigations, mainly on single-storey one-bay reinforced concrete infilled frames, which are discussed in the following section. It can be seen from Table 1 that the composite system, consisting of RC frames infilled with bricks, exhibits higher load capacity, stiffness, energy dissipation, and lateral strength.

Laboratory investigations

A list of reported laboratory studies is given in Table 2, which also contains the material type of the frame and the infill, as well as a summary of the scope and principal findings from each study. Tests were designed such that the influence of some of the parameters, such as the type of material in infill and frame, type of connection, and loading type, could be studied.

The review of the laboratory investigations (Kodur et al. 1994) on the behaviour of infilled frames revealed that the frame – infill interaction plays a significant role in determining the dynamic response of the system. The extent of the interaction was found to vary from partial to full interaction in a number of these studies. Some contradictions on the effect of infill on the behaviour of infilled frames were revealed in these studies. A typical example of these contradictions can be seen from the conclusions reached by Klingner and Bertero (1978) and Govindan et al. (1986) in their studies. Klingner and Bertero, based on experimental results, predicted that the increase in strength and energy absorption would offset the detrimental effects of the possible increase in inertia forces, while Govindan et al. indicated that considerable damage would occur to the infill during the final stages of loading resulting in crushing of the brickwork. This raises doubts regarding the true influence of infills on the behaviour of infilled frames when subjected to seismic loads.

Many of the laboratory investigations were specifically designed to study the beneficial effects of infills. In many cases the extent of the frame – infill interaction was almost complete by a result of the favourable laboratory conditions, such as minimum shrinkage due to ideal conditions for curing,

Table 2. Laboratory tests on infilled frames subjected to lateral loading.

Reference	Type of infilled frame	Scope of principal findings
Wood (1958)	Concrete encased steel frames infilled with bricks	<ul style="list-style-type: none"> • Studied the composite action of frame and infills • Infilled frame can be modelled as a shear-flexural cantilever model
Taniguchi (1960)	Steel frames with masonry infills	<ul style="list-style-type: none"> • Proposed empirical relationships for determining the natural frequencies of an infill-frame system
Sanchanski (1960)	RC frames infilled with brick and concrete infills	<ul style="list-style-type: none"> • Applied lateral load is shared by the shear stiffness of the frame and the stiffness of an equivalent compression strut • Proposed a simplified model to analyse the composite system
Polyakov (1960)	Steel frames with brick masonry	<ul style="list-style-type: none"> • Confirmed the validity of the concept that the effect of infills is equivalent to that of a compression diagonal strut
Holmes (1961)	Steel frames infilled with bricks	<ul style="list-style-type: none"> • Infills can be accounted by treating them as an equivalent strut • An approach to compute ultimate strength and deflection of an infill system was recommended
Mallick and Severn (1968)	Steel frames with brick panels were subjected to ground motion in a shake table	<ul style="list-style-type: none"> • Shear connectors increase the energy of the infilled frame but decrease its ability to absorb energy • Natural frequencies from the proposed two models, a shear cantilever and a shear-flexural cantilever models, compared well with experimental data
Smith and Carter (1969)	Steel and RC frames with brick and concrete blocks respectively	<ul style="list-style-type: none"> • Infill can be replaced by an equivalent diagonal strut
Mainstone (1974)	Steel frames with masonry infills (full as well as scaled models were tested)	<ul style="list-style-type: none"> • Truss approach can be used to analyse the infilled frames with lateral loading • Use of diagonal strut should be restricted to the calculation of first cracking load only • Presence of initial gaps between frame and infills strongly influences the response of infilled frames
Smolira (1973)	Steel frame infilled with brick infills	<ul style="list-style-type: none"> • Proposed an improved strut model based on truss approach • Creep of the wall, arching of infills, and nonhomogeneity of materials influence the response • Proposed a modified strut model to account for bending deformations and initial gaps between frame and infill
Wakabayashi (1977)	Tests and observations of actual buildings during earthquakes	<ul style="list-style-type: none"> • Infills play significant role on the response of infilled frames during actual earthquakes
Velkov and Simeonov (1977)	Steel RC frame and brick infill	<ul style="list-style-type: none"> • Provision of soft elastic material at the interface of frame and panel absorbs frame drifting without transferring forces to the panel
Klingner and Bertero (1978)	RC frame infilled with reinforced concrete panels	<ul style="list-style-type: none"> • Infilled frames are superior to bare frames with respect to energy dissipation and resistance to incremental collapse • The benefits of increase in strength and energy absorption capacities, provided by the infills, far exceed the detrimental effects of possible increase in inertial forces
Srinivasa Rao et al. (1982)	RC frames and brick infills with openings	<ul style="list-style-type: none"> • Constructing the infills first and then the frames improves the bonding at the interface
Govindan et al. (1986)	Seven-storey one-bay RC frame with brick infill	<ul style="list-style-type: none"> • Considerable damage occurs to the infill, during the ultimate loading phase, resulting in crushing and spalling of brickwork
Minami (1987)	12-storey and steel RC frames and lightweight concrete-brick infills	<ul style="list-style-type: none"> • Earthquake observations on full-scale building indicated varying periods from time to time over a time-span of 5 years • Variation of periods was attributed to changing stiffness due to ageing effects and the amplitude of structural response
Dawe and Seah (1989)	Steel frames infilled with concrete block masonry	<ul style="list-style-type: none"> • The strength and stiffness of infilled frames can be improved by reinforcing the infill panel • Panel-to-frame interface conditions influences the response of an infilled frame

Table 2 (concluded).

Reference	Type of infilled frame	Scope and principal findings
Dawe et al. (1989); Sofocleous (1988)	Steel frames infilled with concrete block masonry	<ul style="list-style-type: none"> • Gradual degradation of infill occurs in moderate earthquakes while fast degradation occurs during strong earthquake • Infilled frame resisted ground motions of the order of 0.5g without major damage, while bare frames failed due to the ground motion of 0.1g
Yamazaki et al. (1990)	Full-scale tests on five-storey reinforced concrete masonry building	<ul style="list-style-type: none"> • Significant portion of the transverse walls contributed to the overall load transfer to the load bearing frames • The failure mechanism was governed by the formation of flexural yield hinges at the base of the first-storey walls
El-Qualí et al. (1991) Carydis et al. (1992)	Steel frame with masonry infills RC frame and brick infill	<ul style="list-style-type: none"> • Proposed numerical models for the nonlinear dynamic analysis of infilled frames • The gaps, created due to shrinkage, between infill and the frame leads to large vertical forces for any out-of-plane deformation of the wall • Shrinkage gaps must be filled with nonshrinkable grout after about a week of the construction of the wall
Pires and Carvalho (1992)	RC frames and brick masonry infills	<ul style="list-style-type: none"> • Mode of failure is dependent on the construction procedure • Construction procedure influences the cracking, strength, and initial stiffness

point loading, low frame span to height ratios, and no openings. The same conditions cannot be expected in practice, where infilled frames will have characteristics such as greater shrinkage, varying distributed load throughout the height of the frame, higher frame span to height ratios, and door and window openings. This was recognized by some researchers (Minami 1987; Yamazaki et al. 1990) who resorted to observations on full-scale buildings. Other researchers have commented that some of the limitations of the laboratory studies, such as using infilled frames with impractical characteristics, can be overcome using analytical models.

Analytical studies

The different models used for the analysis of infilled frames are shown in Table 3, together with the steps associated in the analysis. Of the different methods, the stress function method is the simplest, while the finite element method is the most complex and can also be used for nonlinear analysis. Results from the analysis, from any of the methods listed in Table 3, depend on the assumptions made and the idealization of the structure used in the analysis. In the plastic method of analysis, only the ultimate collapse load can be determined, and very little information about the deflections, strains, and stresses can be obtained. A nonlinear analysis, which is capable of predicting realistic behaviour of an infilled frame, is recommended only for important engineering structures, such as tall buildings located in high seismic areas, because of the complexity and effort involved in the analysis.

From the review of the previous analytical investigations, it was found that while static loading on infilled frames has received considerable attention, comparatively few analytical studies have been reported with actual seismic loading (Kodur et al. 1994). This could be attributed to the complexity involved in the dynamic analysis. In the earlier investigations, infills were modelled as diagonal struts, while in recent years, the finite element method has been used to trace the response of the infilled frame subjected to varying lateral loads. The empirical relations proposed by researchers, based on analytical studies, can be used in the preliminary design calculations. Further, the review indicated that many codes of practice, which do not recognize the effect of infill panels, recommend the calculation of base shear as a function of the natural period of the structure computed by taking only the frame into consideration.

The New Zealand masonry code (Standards Association of New Zealand 1990) recognizes the effect of infills in that it specifically requires the interaction of all structural and nonstructural elements which, due to seismic displacements, might affect the response of the structure or the performance of nonstructural elements to be considered in the design. The design provisions in this code are largely governed by seismic load considerations and provide satisfactory structural performance during major earthquakes. The code requires special consideration of the infill to ensure diagonal bracing action when structural modifications result in openings. The provisions for structural design of masonry in Canada are governed by Canadian Standard CAN-S304-M84 (CSA 1990). The specified loads, load effects, and load combinations are computed according to the requirements of the National Building Code (NBC 1990), and the code specifies minimum reinforcement to be provided in the masonry walls.

Table 3. Analytical methods for the analysis of infilled frames.

Method (reference)	Salient features
Stress function method (Polyakov 1960)	<ul style="list-style-type: none"> • The panel and frame elements of infill panel are assumed to resist a percentage of the total load • The load carried by infill and frame is estimated through an iterative approach • The analysis can be carried out using hand calculations; however, the method is approximate
Equivalent diagonal strut method (Smith 1967; Sobaih and Abdin 1988)	<ul style="list-style-type: none"> • The infill is idealized as diagonal struts, and the frame is modelled as beam or truss elements • Frame analysis techniques are used for the elastic analysis • The idealization is based on the assumption that there is no bond between frame and infill
Equivalent frame method (Liauw 1972; Liauw and Lee 1977)	<ul style="list-style-type: none"> • Frame–infill composite system is replaced with an equivalent frame, and equivalent transformed properties are established • Elastic analysis is carried out using beam elements • Idealization is suitable for specifying varying properties or to account for openings
Finite element method (Mallick and Severn 1968; Riddington and Smith 1977)	<ul style="list-style-type: none"> • Infilled-frame system is idealized as panel elements, beam elements, and interface elements to simulate the structural interface • Interface conditions can be properly simulated by adjusting the properties of interface elements • The analysis requires the use of a computer, but detailed results can be obtained
Plastic method of analysis (Liauw and Kwan 1984, 1985)	<ul style="list-style-type: none"> • The frame–infill system is idealized as either integral, or semi-integral, or non-integral frame, depending on the interface conditions • Plastic collapse load corresponding to different possible mechanisms is determined

Table 4. Damping ratios for reinforced concrete and steel structures.*

Form of construction	Damping ratio, β (%)	
	Service	Ultimate
Reinforced concrete core, cantilever floor, lightweight cladding	1.6	2.2
Reinforced concrete columns, slab floors, few internal walls	3	7
Reinforced concrete frame, few internal walls	3	7
Reinforced concrete frame, shear walls	3	8
Reinforced concrete shear core and columns, some internal walls	4	12
Reinforced concrete frame, some internal walls	4	12
Reinforced concrete all forms, many internal walls	5	16
Steel frame, no internal walls	0.5	0.7
Steel frame, few internal walls	2.5	6
Steel frame, many internal walls	4	15

*Source: Cook 1985.

Very few guidelines for the practicing engineers, for the design and analysis of infilled frames, can be derived from the previous analytical studies. Recently, some researchers (Vintzeleou and Tassios 1989) have called for developing simplified analytical models which can be used by practicing engineers for the design and analysis of infilled frames. Efforts are being made for the development of simple guidelines that could be used by the practicing engineers in the design of reinforced masonry in all seismic zones (Noland 1990).

Simplified analysis technique

In the analysis technique proposed herein, the presence of infills is accounted for in all three stages of the analysis, namely in computing the seismic load, in determining the forces in the members, and in determining the strength of the different components of the composite system. The steps associated with the seismic design and analysis of infilled frames are illustrated in the flow chart shown in Fig. 1. Initially, the design and the seismic response spectra are established from codes. The infilled frame is idealized as described in design guidelines, and a dynamic analysis is

carried out to determine the dynamic properties. These properties are used to compute the base shear through a modal analysis procedure. The vertical structural irregularities which arise from nonuniform distribution of infills are accounted for by the structural irregularity parameter, a_r , which is estimated for the infilled frame; if $a_r < 0.5$, the vertical distribution of the infills is modified and the above steps are repeated.

A static analysis of the infilled frame, with all loads, is performed and the member forces in the infill and the frame members are estimated. The columns, beams, and infills are designed for these forces. The strengths of the members are estimated, under different failure modes. If these strengths exceed the design forces, the design is said to be safe. If the design forces exceed the strength, then the member sizes are modified, and the above procedure is repeated. The detailed procedure to be followed in each stage of the analysis is described in the following sections.

Seismic load

To accurately predict the seismic loads, the dynamic properties of the structure must be known. The infilled frame is

Fig. 1. Steps associated with the seismic design of an infilled frame.

idealized as recommended in design guidelines, and the equivalent properties of the infilled frame or the diagonal strut are established. A dynamic analysis is performed, and the natural period (T), natural frequency (ω), and mode shapes (ϕ) are determined. In the analysis, it is sufficient to consider only the first three modes, since higher-order modes do not significantly alter the response of the frame (Smith and Coull 1991) for buildings less than ten storeys high. The dynamic properties thus established are used to determine the base shear due to the seismic load through modal analysis.

The earthquake response spectra, showing the acceleration (S_a'), velocity (S_v'), and displacement (S_d'), corresponding to an earthquake is selected from design codes. The design value of the peak ground acceleration at the site of the building location is obtained from codes (NBC 1990). The response of a structure depends on the damping present in the structure, and the value of the structural damping ratio for the infilled frame under consideration is obtained from Table 4. The values of S_a' , S_v' , and S_d' , corresponding to a structural damping ratio and a natural period, are obtained from the selected response spectra in all three modes. The design values of S_a , S_v , and S_d , in all the modes, are computed by multiplying the respective values with peak ground acceleration.

In the modal analysis, to account for the effect of the infill, an equivalent frame is used to estimate the seismic

load. The properties of the equivalent frame are estimated and the maximum base shear is computed as described by Kodur et al. (1994). The maximum base shear thus obtained is distributed as lateral forces to different storeys, based on their masses. At each storey, the lateral forces are further distributed to different columns of the corresponding storey.

Static analysis

The second stage in the seismic design is to establish the response of the infilled-frame composite system under different loading combinations. The different loads to be considered in the analysis are computed as recommended in codes of practice. Torsional loads that might arise from a nonsymmetrical distribution of the infills are calculated. The total load acting on the infilled-frame system is established, with due consideration to any load factors and load combination factors, as given in codes of practice.

The infilled frame is idealized, and an elastic analysis is carried out. The member forces in the columns, beams, and infills and the resulting deflections are computed. These member forces are used as the design values, and the infills and frame members are designed as recommended in codes of practice.

Strength of frame and infills

Having determined the forces in the frame members, the next step is to check the adequacy of the infilled-frame system for the induced forces. The cracking and failure modes are to be considered in carrying out these checks for both concrete frames and infills, since increased cracking leads to crushing of these members. The design of the frame and infill is satisfactory when the computed strengths for anticipated modes of failure exceed the design forces in these members. In the strength calculation for the seismic loading, only the failure modes corresponding to the columns and infills are considered in this section, because the beam stiffness has very little effect on the behaviour of infilled frame (Smith and Carter 1969). However, strength checks for beams, corresponding to usual failure modes, should be carried out during the course of the analysis.

The possible modes of frame failure that result from the presence of seismic loads are tension failure of the windward columns, or shear failure of the columns and beams (Smith and Carter 1969). If the frame strength is sufficient to withstand collapse by one of these modes, the increasing load eventually produces failure of infills. In concrete infills, the usual failure modes are tension cracking along the compressive diagonal, followed by crushing near one of the loaded corners. In the case of a relatively stiff frame, crushing might occur in the interior region of the infill. For infills constructed with brick masonry, shear failure along the mortar joint to masonry panel should be considered. The strength of the columns and infills under different cracking and failure modes is computed, using empirical relationships developed by previous researchers (Govindan et al. 1986; Smith and Carter 1969), as described by Kodur et al. (1994).

Design guidelines

Implementation of the proposed analytical procedure in the design process requires detailed knowledge of some of the

Fig. 2. Idealization of an infilled frame: (a) diagonal strut; (b) equivalent frame.

factors that influence the behaviour of infilled frames. Some of the factors that are relevant to the seismic analysis of infilled frames are discussed in the following, with practical design recommendations.

Idealization of infilled frames

In the proposed approach, the infill is accounted for in the static and dynamic analysis by idealizing the infilled frame as either a frame-diagonal strut system or an equivalent frame system. In the frame-diagonal strut system, the infill is modelled as an equivalent diagonal compressive strut. While in the equivalent frame system, the action of the infill and that of the frame are combined to obtain an equivalent frame. The frame-diagonal strut idealization is suitable for frames with no shear connectors, while the equivalent frame idealization can be used in cases where there are shear connectors or openings. The two idealizations for a typical infilled frame are shown in Fig. 2. When the frame-diagonal strut idealization is used, the columns and beams of the frame are modelled as beam elements, with three degrees of freedom at each node, namely rotation and two displacements, while the diagonal strut is modelled using truss elements. For the case of the equivalent frame idealization, beam elements are used. Shear deformations and axial deformations should be included for both idealizations, since these effects are predominant when the infilled frame is subjected to seismic or other lateral loads.

When additional loads, induced by irregular geometry or torsional effects, are to be applied in between the storeys, the analysis can be facilitated by using more than one beam element for each column and beam. This approach is also useful when varying properties along the length of the frame members are specified or when deflections and rotations at points other than at beam-column joints are to be obtained.

Diagonal struts

When the infill is modelled as an equivalent diagonal strut, the contact length parameter (λ) and width (w) are computed using the relationships proposed by Mainstone (1974):

Fig. 3. Dimensions of an idealized infilled frame: (a) diagonal strut model; (b) equivalent plane frame model.

$$[1] \quad l = \sqrt{\frac{E_i t \sin(2\theta)}{4E_f I_c h'}}$$

$$[2] \quad w = 0.175 \lambda^{-0.4} d'$$

where E_i is the modulus of elasticity of the infill material, E_f is the modulus of elasticity of the frame material, I_c is the moment of inertia of column, and t is the thickness of infill. The variables h , h' , d' , and θ are shown in Fig. 3a, which shows the analytical idealization of an infill panel as an equivalent strut. Knowing the values of λ and w , the other design parameters required for the analysis, namely area of infill ($A_i = wxt$), length of contact (λh), and panel ratio (l'/h') can be determined.

Equivalent frame

When an infilled frame is idealized as an equivalent frame, as shown in Fig. 3b, the effect of the infill is accounted for by modifying the properties of the frame. The properties of the equivalent frame are computed using the procedure

Fig. 4. Influence of decreased natural period of infilled frame on design spectrum.

recommended by Liauw (1972). It should be noted that the corner parts of the infill are used twice to calculate the moment of inertia of the beams and columns of the frame. This tends to increase the stiffness of the frame, which is to be expected, since the corners of the infill stiffen both the beams and columns.

Damping ratios

Damping plays a significant role in determining the behaviour of an infilled frame subjected to seismic loads. The amount of damping in a structure depends on the magnitude of the displacements and the stress levels. Cook (1985) has given typical values of damping ratios (β) for different types of concrete and steel frames, both at service and at ultimate conditions. These values are reproduced in Table 4. It can be seen from Table 4 that the damping ratio is higher for ultimate load levels, and that the presence of infill increases the damping, for both steel and reinforced concrete frames, at service and ultimate conditions. The ultimate damping ratio is to be used when the response of the structure is traced from precracking to collapse using a nonlinear analysis. For an elastic analysis, appropriate damping ratios corresponding to the service state should be used.

Uncertainty in design

When infills are included in the analysis, the natural period of the structure decreases owing to increased stiffness. The effect of this decreased natural period on the base shear value depends on the characteristics of the expected ground motion. Therefore, the addition of infills might be favourable or unfavourable from the point of base shear, depending on the frequency content of the ground motion (Vintzeleou and Tassios 1989).

However, during the course of the design, only unfavour-

able effects of the infill on the natural period of the building are to be considered. This is because the effect of a first earthquake might cause some damage to the infill, resulting in a decrease in the stiffness of the frame. A decreased stiffness results in an increased period. Consequently, during a subsequent earthquake, the frame might attract higher forces. A typical case of the above situation is illustrated in Fig. 4. The natural period of the frame, T_{BS} , reduces to T_{IS} , when the infills are accounted for, resulting in an increase in seismic acceleration from a_I to a'_I for the first (I) earthquake. However, due to this earthquake, the infills are slightly damaged resulting in a decreased stiffness, thereby leading to a decrease in the period of T_{BS} . When the second earthquake occurs near the site of this frame, the peak acceleration would be a_{II} instead of a'_{II} . So the design spectrum for this frame should be drawn by considering both cases as represented by the elastic design spectrum in Fig. 4.

Structural irregularities

Both horizontal and vertical structural irregularities arise if the infills are not uniformly distributed in plan and elevation. These irregularities influence the seismic behaviour considerably. Vertical irregularities arising from the nonuniform distribution of infills along the height of the building might cause considerable variation of the difference between the available and required shear resistances from floor to floor, leading to an increased ductility demand.

The ratio between the minimum i_j and the average value of i is called the regularity index, a_r , where i_j is computed as the ratio between the available shear resistance, V_{Rj} , and the required shear resistance, V_{Sj} . For vertically regular buildings, a_r is close to unity. If the value of a_r is less than 0.8 for the j th storey, then additional design steps to account for reduced ductility are to be used (Vintzeleou and Tassios

1989). Buildings with $a_r < 0.5$ should be modified so as to get a higher value of a_r , since the actual seismic behaviour of highly irregular buildings is unpredictable, even when using elaborated mathematical models (Vintzeleou and Tassios 1989). It is recommended to design the structures with a minimum value of a_r of 0.8.

The horizontal irregularity of the building arising from a nonuniform distribution of infill walls in-plan introduces additional torsional seismic effects. For computing horizontal irregularity, due to the nonsymmetrical distribution of infill walls in-plan, an equivalent stiffness should be used when determining the coordinates of the centre of stiffness. The distance between the centre of the masses and the centre of stiffness should be used to calculate the torsional effects on infilled frames.

Torsional effects

Torsional effects result from lateral forces applied at the centre of the floor mass, at an eccentricity from the centre of rigidity. Additional torsional effects may result during the dynamic response of the structure, if the assumed stiffness in the analysis differs from the actual stiffness. The torsional effect of an infilled frame, due to the shift of the centre of rigidity, is estimated to be similar to that for a bare frame (Paulay and Priestley 1992). The difference between the actual and assumed stiffnesses of the frame can be eliminated by using the equivalent stiffness of the infilled frame in the analysis.

Computational aids

Any frame analysis program, which has static and dynamic analyses options, can be used for the design of infilled frames subjected to seismic loads. The frame analysis, both static and dynamic analyses, can be carried out using the frame analysis program; and the remaining steps associated with the proposed analytical procedure (Fig. 1) can be carried out on a spreadsheet. These steps include calculating the base shear using a modal analysis, computing the equivalent properties, designing the infill-frame members, and determining the strength of the members. Shear deformations and axial deformations should be accounted for in the analysis. The use of a spreadsheet software for these calculations has the advantage of simplicity and ease in modifying the design for different cases.

Construction guidelines

Available experimental observations indicate that it is possible to achieve a nonseparating, tight interface condition by following certain steps during construction. The following guidelines can be implemented during the construction phase in order to get a good frame to infill monolithic action, thereby improving the behaviour of the composite system (Thiruvengadam 1985; Velkov and Simeonov 1977).

1. Proper care should be taken to check the water absorbent quality of bricks, and the bricks should be soaked well before placing them in position in order to reduce the shrinkage of masonry and the resulting interface gaps.

2. A rich mortar when applied at the frame to masonry interface, with an expansive-type cement, improves the bonding and minimizes the initial gaps.

3. Shear connectors should be provided in the form of

protruding steel reinforcement, taken from the column members and anchored in the courses of masonry. Vertical dowels from the supporting beam when connected to the infill also improve the composite action.

4. The bonding at the interface can be improved significantly by constructing the brick masonry first, and then casting the reinforced concrete frame using masonry as part of formwork for concrete. The filler walls and the structural frame may be constructed in stages. This practice, though not practical in North American construction, was found to be beneficial (Srinivasa Rao et al. 1982).

5. Hollow block masonry, when used for constructing masonry infill walls, can be used to obtain good connection, since the reinforcement taken from the frame members can be anchored inside the void of the blocks which can be subsequently filled with plain concrete.

6. The doorway openings should be placed preferably at the centre of the panel in order to allow the diagonal strut action to be developed in the infilled frame. It should be noted that the infills with large openings do not behave as solid panels and the compressive strut action might not be obtained in such situations.

7. Shattering and spalling of masonry infills leading to explosive failure during an earthquake can be avoided by adding well-anchored light wire meshes on both faces of the infill walls.

8. The vertical load imposed to an infilled frame improves the confinement of the infill, which leads to increased strength and improvement in the overall behaviour of the infilled frame.

9. If the infills are not connected to the frame, then soft elastic material can be used at the interfaces of the frame and the panel to absorb the frame drifting and to buffer the transfer of forces to the panel.

The infilled-frame system, damaged by the earthquake, can be repaired and strengthened in order to resist future seismic loadings. Zarnic et al. (1986) have given some practical methods for the repair of such structures.

Numerical example

The proposed analytical procedure was applied to the seismic design and analysis infilled frames and results from a typical infilled frame example are discussed in the following. Detailed calculations are presented in Kodur et al. (1994).

The analysis was carried out for the infilled frames located in a three-storey three-bay reinforced concrete building. The building was assumed to be located in a seismic zone with peak ground acceleration of 0.4g, and the analysis was carried out for three cases. In the first case, Case A, the analysis was carried out by taking the contribution of the frame acting without infill, or the bare frame. The effect of infill throughout the frame is accounted for in Case B, which represents an infilled frame. In Case C, the openings present in the infill are considered.

The dynamic properties of the building, determined using the frame analysis computer program with the recommended idealization, are compared in Table 5. It can be seen from the table that the effect of the infill in Case B significantly reduces the natural period. The presence of openings in Case C results in a slightly higher natural period as compared to that in Case B. As expected, the natural period in all three cases

Fig. 5. Variation of base shear for three cases of frame idealization. **Table 5.** Dynamic characteristics for the frame.

Property	Bare frame (Case A)			Infilled frame (Case B)			Infilled frame with opening (Case C)		
Mode No.	1	2	3	1	2	3	1	2	3
Circular frequency (rad/s)	10.0	32.2	55.6	23.4	88.8	93.3	20.2	78.6	92.8
Natural frequency (Hz)	1.59	5.12	8.84	3.72	14.1	14.9	3.21	12.5	14.8
Period (s)	0.627	0.195	0.113	0.269	0.071	0.067	0.311	0.08	0.07
Mode shape									
1	0.329	-1.127	2.446	0.234	1.147	0.286	0.232	-1.14	-0.27
2	0.743	-0.778	-2.365	0.636	-1.03	0.214	0.637	-1.07	-0.27
3	3	1	1	1	1	1	1	1	1

Table 6. Equivalent lateral forces and base shears for the frame.

Property	Bare frame (Case A)			Infilled frame (Case B)			Infilled frame with opening (Case C)		
Mode No.	1	2	3	1	2	3	1	2	3
Maximum probable base shear		99 772			163 507			163 206	
Base shear	97 718	19 145	6245	161 058	24 800	13 410	160 784	25 818	10 878
NBC base shear		186 000			186 000			186 000	

NOTE: All units are in Newtons.

decreases with higher-order modes. The mode shapes for cases A, B, and C varied widely from one case to the other, indicating that the variation in the behaviour of an infilled frame depends on the idealization used in the analysis.

The maximum probable base shear and the base shears in the three modes are presented in Table 6 for the three cases of analysis, together with the base shear as per National Building Code (1990). It can be seen from the table that the second and third modes have little influence on the maximum probable base shear values and confirms that higher-order modes need not be accounted for in seismic design and analysis. It can also be seen from the table that the maximum probable base shear is significantly higher in cases B and C,

indicating that the presence of infills attracts higher seismic loads. The higher shear can be attributed to the increased seismic acceleration, which results from the reduced natural period. The base shear calculated from NBC is higher than that obtained from modal analysis for all three cases. The NBC formula does not recognize the effect of infill panels and is very conservative when compared with the base shear of the bare frame. The effect of infills can be further seen in Fig. 5, which shows the variation of shear, resulting from seismic loads, in different storeys corresponding to three frame idealizations and that from NBC.

Figure 6 shows the plot of horizontal storey deflections for three cases of frame idealization. It can be seen from the

Fig. 6. Variation of storey deflections for three cases of frame idealization.

figure that the top-storey deflection of the bare frame is nearly three times higher than that of the infilled frame. This increased deflection is in spite of the smaller magnitude of applied lateral forces at each storey. The deflections increase for Case C because of the reduction in stiffness from the presence of an opening.

Conclusions

The following conclusions may be drawn from the investigation reported herein.

1. The behaviour of an infilled frame is dependent on the properties of frame and infill; hence, the response of such frames should be based on overall frame to infill composite action rather than on isolated bare frame behaviour.
2. The proposed analytical procedure accounts for the effect of infill in all stages of analysis: in computing the seismic loads, in predicting the response of the infilled frame, and in determining the strength.
3. The proposed analytical procedure can be implemented in the normal course of design and uses readily available computational tools.
4. The performance of an infilled frame can be improved by implementing recommended guidelines during the construction phase. These steps not only help in achieving the better composite behaviour, but also reduce the analytical complexity and uncertainty.

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