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EVALUATION AND ANALYTICAL VERIFICATION OF SHAKING TABLE DATA FROM INFILLED FRAMES

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ABSTRACT

In a comprehensive multi-year experimental study carried out at the U.S. Army Construction Engineering Research Laboratories (USACERL), several half-scale specimens consisting of reinforced concrete frames (bare and with masonry infilling), were subjected to simulated earthquake motions using a shaking table. In- and out-of-plane motions were applied to virgin specimens, previously damaged specimens, and repaired specimens. In the theoretical study reported here (carried out at the University of Texas at Austin), the experimental data obtained by USACERL were used to evaluate the in-plane behavior of infilled frames. Load-displacement characteristics were obtained; and maximum loads, deflections and internal strains were measured and assessed. Dynamic response was predicted using various mathematical idealizations. Simplified analytical idealizations were developed to predict the strength and stiffness of infilled frames. Results from shaking table tests with low levels of base accelerations were not useful for evaluating the strength and stiffness of the specimens. However, results from tests with higher base shears were generally useful. The nonlinear response of infilled frames, excited in-plane, was reasonably well predicted using an equivalent SDOF idealization whose nonlinear hysteretic behavior had first been obtained using a finite element model.

KEYWORDS

Codes; Earthquakes; Infilled Frames; Masonry; Rehabilitation; Seismic; Structural Analysis

INTRODUCTION

A recent inventory of essential and high-risk buildings used by the U.S. Army showed that nearly 40% of them were classified as reinforced concrete frames with infill shear walls (Bashandy et al. 1995). Generally, the infill panels of these buildings were not intended to be part of the structural system. Extensive experimental and analytical research on analysis, design, and behavior of infilled frames has been conducted worldwide during the last three decades. Based on the results of such investigations, a number of design approaches have been proposed. However, most data have been obtained from quasi-static tests; the dynamic response of these structures has not been completely assessed. Because of this, in 1992 the U.S. Army Construction Engineering Research Laboratories (USACERL) initiated a comprehensive multi-year research program to develop methods for assessing the seismic vulnerability of existing infilled-frame structures. From early 1992 through May 1993, USACERL carried out a series of shaking-table tests on half-scale models of reinforced concrete frames, infilled with unreinforced clay masonry. The objective of those tests was to aid in the development of engineering models for estimating the load-deflection behavior of the infilled frames under earthquake ground motions, considering elastic and inelastic response, in-plane and out-of-plane response, and the effects of damage due to in-plane excitation on the out-of-plane strength. Some tests were intended to assess the effectiveness of rehabilitation methods for infills with low out-of-plane strength. Extensive data were gathered during that test program, including accelerations, displacements, and internal deformations. As part of the research study reported here, those data were evaluated using state-of-the-art analytical models and also simplified engineering design models.

REVIEW OF PREVIOUS RESEARCH

Tests under In-Plane Loading

Most previous experimental work on infilled frames has been performed on one-story, one-bay specimens, although a limited number of investigations have included multi-story, multi-bay frames. Parameters studied have included: the frame material (steel and concrete); the infill material (clay brick, hollow clay tile, and concrete block); the type of failure mechanism (infill diagonal cracking, infill crushing, column shear, and column hinging); scale effects (1/8- to full-scale); confinement of the infill by adjacent panels; and relative frame/infill strength and stiffness (Angel et al. 1994). Results show that for strong and stiff frames with weak infills, system behavior is dominated by the frame: the panel cracks, while adapting to the frame deflection. In contrast, the behavior of weak frames infilled with strong panels is controlled by the infill, which cracks in an "X" pattern and may produce a brittle failure of the infill or the columns.

Analytical Studies for In-Plane Loading

The shear beam model is probably the simplest approach for infilled frames; however, stiffness at cracking of the infill is generally overestimated (Thomas and Klingner 1990). In another common idealization, the infills are replaced by equivalent diagonal compression struts (Holmes 1963; Stafford Smith 1966; Riddington and Stafford Smith 1978). A similar but more sophisticated approach uses multiple struts (diagonal and vertical) to model the infill panels (Thiruvengadam 1985). More elaborate finite-element idealizations have been also used. Initially, only linear elastic masonry behavior was considered; frame/infill interaction was neglected. Other studies then included frame-infill separation and the loss of friction along the remaining contact length (Riddington and Stafford Smith 1977). Recently, brick-size finite elements linked by mortar elements have been used (Page 1978). Finally, inelastic analyses have considered cracking, tension stiffening, and compression softening of the masonry .

USACERL SHAKING TABLE TESTS

Overview of Experimental Program

Two sets of test specimens were constructed at USACERL. The first set, referred to as "weak frames," was intended to represent buildings designed by the 1956 ACI Code and old construction practices. A second set of specimens, referred to as "strong frames," was designed by the 1989 ACI Code, and was intended to represent modern building construction. The experimental program consisted of a series of dynamic tests with increasing ground motions applied to each set of specimens. Each specimen consisted of a reinforced concrete frame (strong or weak, bare or infilled, and tested in- or out-of-plane) supported by a foundation beam that was attached to the shaking table. An overall view of a typical infilled frame specimen is shown in Figure 1. For each type of frame, the sequence described below was followed.

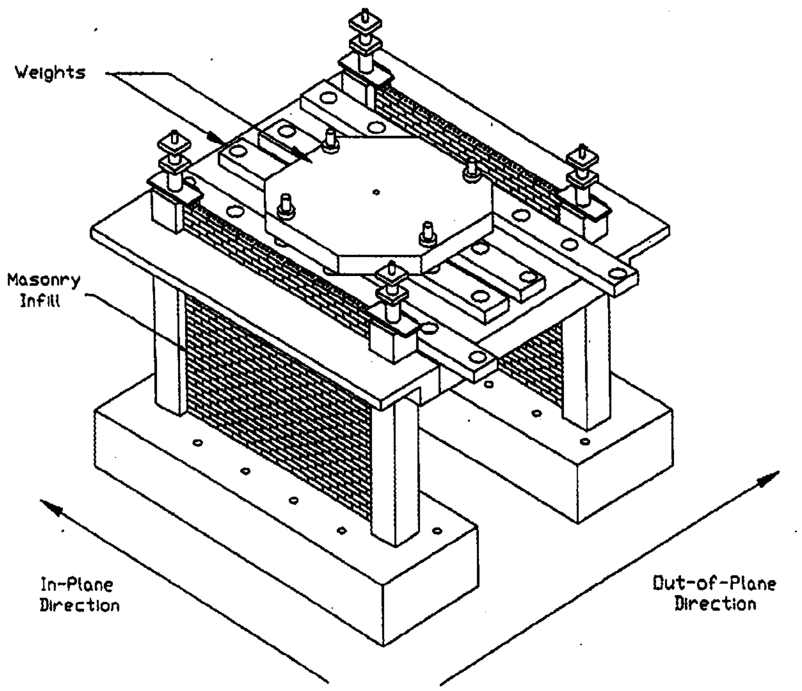

Figure 1 *Overall View of a Typical Specimen*

First, a bare frame specimen consisting of two parallel frames was tested in-plane. Gradually increasing levels of ground motion were applied parallel to the frames. Their dynamic properties were measured, and damage to them was assessed. The frames were then infilled with masonry, and gradually increasing levels of ground motion were again applied. The specimens' dynamic properties were again measured, and the maximum ground motion was gradually increased until the infills cracked. Finally, one infilled frame of the specimen was rotated 90 degrees and subjected to out-of-plane ground motions until severe cracking occurred.. No specimen was tested in-plane after out-of-plane excitations had been applied; therefore, the effects of prior out-of-plane excitation on in-plane response cannot be assessed. In all cases, random vibrations were applied to the specimens to measure their fundamental frequency of vibration, from which their stiffnesses could be readily estimated. For the strong-frame specimen, the infill was repaired after the out-of-plane excitation and subsequently re-tested to evaluate the effectiveness of the repair method. The weak-frame specimen was not repaired. Finally, a strong infilled frame, to which no prior in-plane excitation had been applied, was tested out-of-plane until severe damage was apparent.

Description of Specimens and Test Setup

The specimens were half-scale models of bare and infilled reinforced concrete frames. Each specimen consisted of two parallel one-story, one-bay frames, connected at their top levels by a stiff concrete slab. The slab was attached to the top beams by transverse steel rods. The frame columns were founded on massive beams that were rigidly connected to the shaking-table floor. For the strong frame the beams were 5 in. wide by 6 in. deep (125 mm × 150 mm), and the columns were 6 in. square (150 mm × 150 mm). For the weak frame, the beams were 4 in. wide by 6 in. deep (100 mm × 150 mm), and the columns were 5 in. square (125 mm × 125 mm). The infills had a height of 32.5 in (826 mm), a thickness of 1.75 in (45 mm), and a height-to-thickness ratio of 18, and were made of half-scale clay brick laid with a Type N mortar conforming to ASTM C270 by proportion. The masonry prism compressive strength was 5000 psi (35 MPa). The compressive strength for concrete was 4000 psi (28 MPa) and for mortar was 2000 psi (14 MPa). Finally, the yield strength of the reinforcement was 62500 psi (438 MPa). Detailing of both longitudinal and transverse reinforcement is given by (Bashandy et al. 1995).

Post-tensioning cables were threaded through each column to increase their axial load, simulating the effects of the gravity loads generated by overlying stories of a multi-story building. In addition, masses of 8.0 kips (36 kN) and 6.0 kips (27 kN) were added to the slab of the strong- and weak-frame specimens respectively; these masses were intended to simulate the lateral inertial forces generated in the full-scale prototype under base excitation. Ground accelerations were input to the specimens using the USACERL Biaxial Shock Testing Machine (BSTM). The foundation beams of the specimens were rigidly attached to the shaking table to avoid sliding of the frames. At very small time intervals, accelerations and displacements were recorded at various locations, and reinforcing-bar strains were measured at critical zones of columns and beams.

Testing Sequence

The first series of tests was performed on strong-frame specimens. The bare-frame specimen was subjected to a series of in-plane ground motions until cracking was observed. Varying levels of axial prestress were applied to the columns of this specimen during the tests. Clay masonry infills were then added to the frame, and a new series of gradually increasing in-plane ground motions was applied to this model until the infills cracked. One infilled frame of this specimen was then rotated 90 degrees, and its tip was fixed with cables to the shaking-table floor. This specimen was subjected to a series of out-of-plane ground motions until severe cracking occurred in the infills. After this, the masonry infill was repaired on both sides by 1/4-inch x 1/4-inch x 23-gage steel wire mesh, covered by a 1/4-inch (6-mm) ferro-cement coating designed for high compressive strength and high workability. The steel mesh was not anchored to the infill nor to the frame; all bond between the infill and the coating was achieved at the coating-infill interface itself. This repaired specimen was subjected to a new series of increasingly severe out-of-plane ground motions, until severe damage occurred. Additionally, random vibration tests were performed on the specimens at intervals, to estimate their dynamic properties.

Behavior under In-Plane Loading

The specimens' responses under in-plane loading were evaluated using curves of tip displacement versus base shear, and reinforcement strains. Dynamic characteristics were also obtained from the results of the random vibration tests. In general, tests with low base acceleration (under 0.5g for bare frames and under 2.0g for infilled frames) were not useful due to the poor precision of the recording devices.

Bare frames responded inelastically. The strong frame cracked extensively, and showed a significant decrease in stiffness (to 30% of the initial stiffness). For the weak frame, tensile yielding of reinforcement was recorded at column faces, and the overall damage level was greater than for the strong frame. The maximum recorded story drift for the strong frame was *0.80%* and the maximum base shear was *2.10W* (*W* is the total weight of the specimen). For the weak frame, the maximum drift was *1.80%* and the maximum shear was *2.80W*. Figure 2 shows a typical load-displacement response of a bare frame.

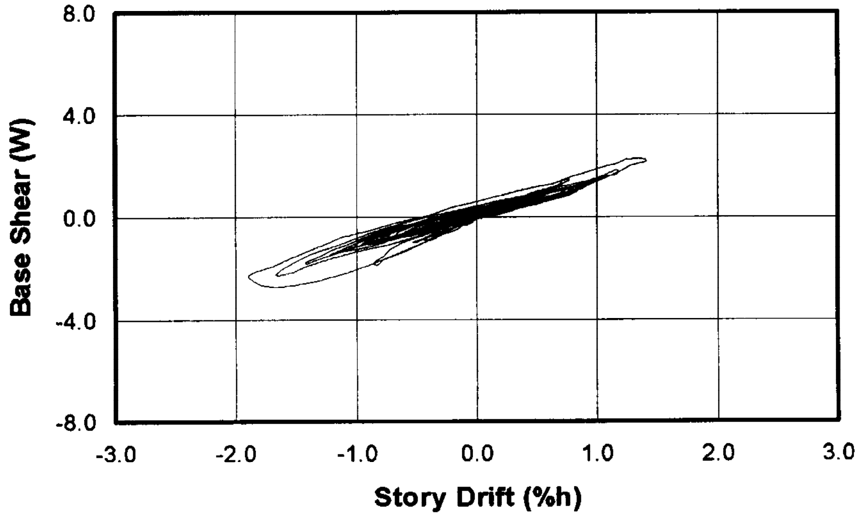

Figure 2 *Typical Experimental Response of a Bare Frame under In-Plane Loading*

After masonry infills were added to the specimens, the maximum base shears recorded were *5.30W* for the strong frame and *7.00W* for the weak frame, while the maximum drifts were 2.00% and 2.50%, respectively. Thus, the strength of the specimens increased by a factor of about 2.5 after adding the infills. Figure 3 shows a typical load-displacement response of an infilled frame.

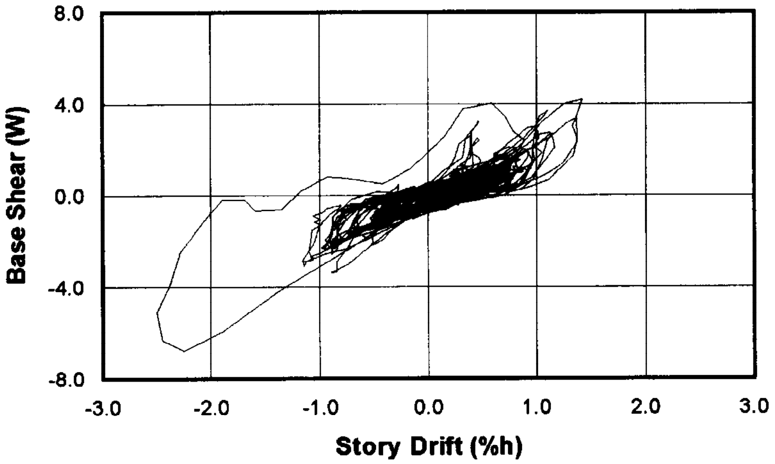

Figure 3 *Typical Experimental Response of an Infilled Frame under In-Plane Loading*

These maximum recorded base shears, however, may not correspond to the specimens' strengths, since they were generally recorded during an isolated hysteretic loop generated by a base acceleration spike, while all other cycles showed lower levels of shear and displacement. In addition, the specimens did not undergo severe damage nor significant yielding of reinforcement; therefore, they may have had additional capacity. Measured displacements were considered too large, particularly for the infilled frames. This was probably due to signal noise, gauge sensitivity, or failure in the data acquisition equipment. Consequently, recorded displacements and stiffness computed using those displacements were not considered reliable. Results from random vibration tests suggest that after the seismic tests, the stiffness of the infilled frames had decreased to less than one-third of the original value.

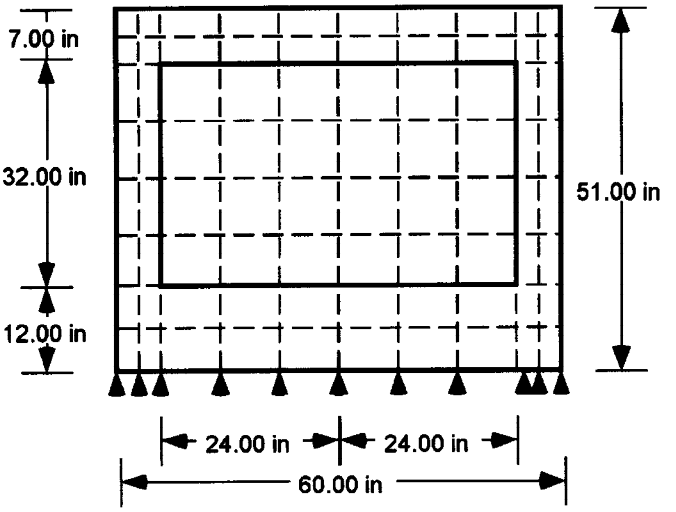

Figure 4 *Finite Element Mesh Used for FEM/I Analysis*

ANALYTICAL IDEALIZATIONS AND SIMPLIFIED DESIGN MODELS

Analysis for In-Plane Loads

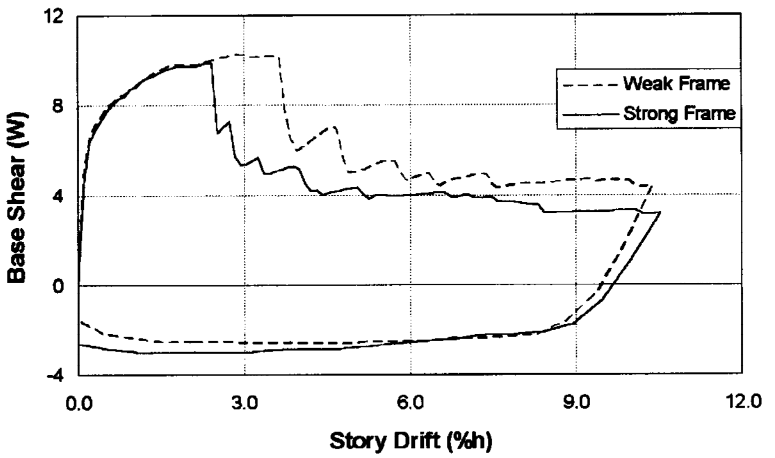

Figure 5 *Pushover Response of Test Infills Given by FEM/I Program*

To predict the behavior of the infilled frames under seismic loads, two recently developed computer programs were used. First, the FEM/I program (Ewing et al. 1987) was used to perform a pushover analysis of the specimen, modeled using the finite element mesh shown in Figure 4. The FEM/I program considers nonlinear behavior, biaxial states of stress, and smeared cracking. Using the FEM/I program, three different idealizations of the specimens were developed. The first model used the actual properties and geometry of the infill. For the second model, the infill elements in contact with the frame elements were assumed to have only 10% of the masonry tensile strength, to simulate the weak interface between the infill and the frame. The last model included only the elements along the equivalent diagonal strut. The monotonic responses of all three models were practically identical (Bashandy et al. 1995). Figure 5 shows the load-displacement response obtained by the FEM/I program, for the two types of test specimens.

The LPM/I program (Kariotis et al. 1992) was then used to calculate the inelastic cyclic response of the infilled frame, modeled as a lumped-mass, single-degree of freedom system. This program used an inelastic degrading spring. The envelope stiffness and strength parameters for the spring were computed based on the monotonic response as previously calculated using the FEM/I program. Figure 6 shows a typical dynamic load-displacement response from the LPM/I program. In general, levels of base shear were estimated closely by the analytical model of program LPM/I. In contrast, analytical displacements were much smaller (one order of magnitude) than those measured experimentally. This discrepancy is believed due to the above-mentioned problems with displacement instrumentation.

Several simplified idealizations using equivalent diagonal struts were studied as part of this research. The method proposed by Stafford Smith (1966) gives the closest prediction of the initial stiffness of single-panel infilled frames. This model accounts for the relative stiffness of the frame and the infill by means of the length of the contact interface, α, computed using Equation 1. In that equation, λ is a dimensionless parameter given by Equation 2.

$$\alpha = \frac{\pi}{2\lambda} \qquad [1]$$

$$\lambda = \sqrt[4]{\frac{E_i\, t \sin\theta}{4 E_f I_c L}} \qquad [2]$$

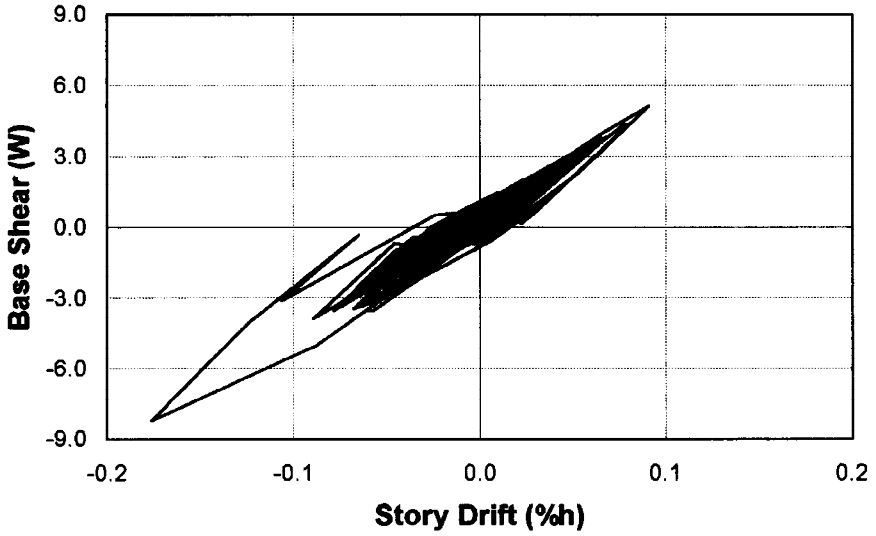

Figure 6 *Typical Analytical Dynamic Response of Infilled Frames under In-Plane Loading, Calculated by LPM/I Program*

In Equation 2, E_i is the infill elastic modulus, E_f is the frame elastic modulus, t is the panel thickness, θ is the angle of the panel main diagonal, I_c is the column moment of inertia, and L is the beam length. Finally, Stafford Smith (1966) related the contact length with the width of the equivalent strut, w, using the curves shown in Figure 7, in which d is the length of the main diagonal, h is the height of the panel, and L/h is the aspect ratio. Using these curves, the area of the strut, A_{dc}, can be computed by Equation 3.

$$Ade = w \cdot t \qquad [3]$$

Equations 1 through 3, together with the curves of Figure 7, give only the initial stiffness of the structure. However, as mentioned before, the results of the dynamic tests, evaluated as part of this study, suggest a reduction in stiffness of more than 60% with in-plane cycling. From static tests, Angel et al. (1994) suggest that stiffness is reduced to half its initial value after cyclic loading.

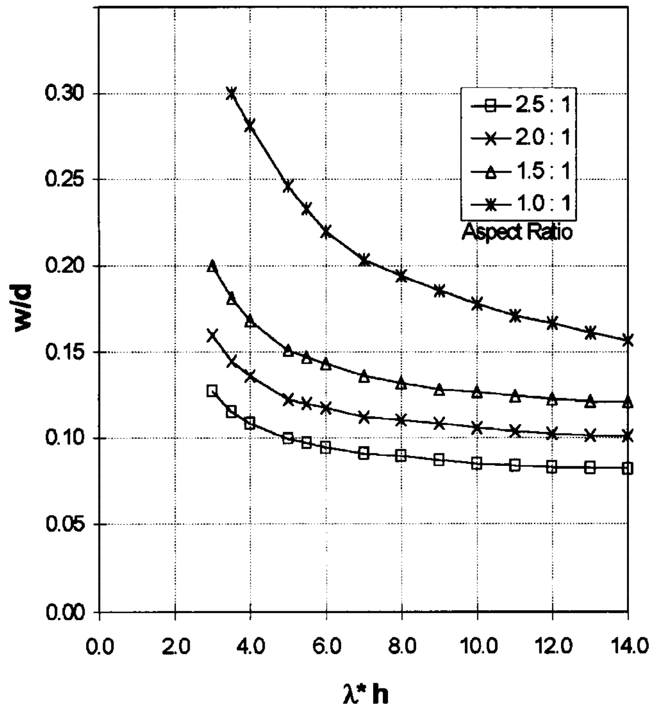

Figure 7 *Width of Equivalent Strut (adapted from Thomas and Klingner 1990)*

Of all the strut models studied, that of Holmes (1963) gave the closest prediction for the in-plane strength of the infilled frame, particularly when the area of the strut, A_{de}, is computed using Equation 3 instead of the fixed value of *d/3* originally proposed by Holmes. In that method, the deformation of the equivalent strut is equated to the shortening of the frame diagonal to obtain the equivalent lateral load that produces the failure of the infill, given by Equation 4:

$$H = \frac{24EI_c e'_m d}{h^3\left[1+\left(\frac{I_c}{I_b}\right)\cot q\right]}\cos q + A_{de} f'_m \cos q \quad [4]$$

In Equation 4, E_f is the frame elastic modulus, θ and d are the angle and the length of the main diagonal of the panel, I_c is the column moment of inertia, I_b is the beam moment of inertia, ε'_m is the infill strain at failure, h is the frame height, and f'_m is the masonry compressive strength.

CONCLUSIONS

Results of recent experimental research on reinforced concrete infilled frames, carried out by USACERL, are presented. In that research, several series of simulated seismic motions were applied by a shaking table, in both in-plane and out-of-plane directions. The infilled frames were up to 2.5 times stronger in-plane than the bare frames, and they sustained many hysteretic cycles of in-plane shaking with no major damage. However, their stiffness decreased to about one-third of its initial value under in-plane cycling. These results confirm previous indications, from quasi-static and from shaking-table tests, that infilled frames can significantly increase the stiffness, strength and energy dissipation capacity of framed structures, even under conditions involving simultaneous in- and out-of-plane inertial forces.

The experimental results were subsequently evaluated at the University of Texas at Austin using several mathematical models. First, the in-plane behavior of the infilled frame specimens under monotonically increasing load was calculated using a nonlinear finite element analysis. The resulting pushover curve was then used to determine the appropriate properties for an inelastic hysteretic model. Finally, that inelastic hysteretic model was used with a lumped-parameter program to calculated the nonlinear dynamic response. Both analyses closely reproduced the form of the experimentally observed shaking-table response. Discrepancies between observed and calculated displacements are believed to be due to errors in displacement measurement.

For in-plane design of infilled frames, several simplified models using equivalent struts were then evaluated. The method proposed by Stafford Smith (Figure 7 and Equations 2 and 3) was found to most closely estimate the initial in-plane stiffness of infilled frames, while a modified version of the method proposed by Holmes (Equation 4) was recommended to estimate their in-plane strength. However, under cyclic loading, the estimated stiffness should be reduced to one-third of this initial value.

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