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IN-PLANE STIFFNESS OF REINFORCED CONCRETE FRAMES WITH MASONRY PANEL INFILL

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Abstract

The effect of the wall aspect ratio, $\alpha = H/L$, beam-to-column inertia ratio, $\beta = I_b/I_c$, and the effect of openings on the in-plane stiffness of reinforced concrete infilled frames has been investigated. Tests were conducted on forty eight one-third scale models of RC frames from which the initial tangent stiffness, K_i, the secant stiffness at first crack, K_c, and the secant stiffness at ultimate, K_u, were determined. Although the three parameters markedly affected the in-plane stiffness of infilled frames, the aspect ratio did not have a significant effect on K_u. A unit increase in aspect ratio resulted in fifty percent reduction of K_c. Although the effect of the beam-to-column inertia ratio on K_c and K_u depended on the opening coefficient, a unit increase in β resulted in more than ten percent increase of the initial stiffness. Regression analyses were performed on test results and yielded empirical formulations which could be used in assessing the stiffness of RC frames infilled with masonry panels.

1 Introduction

Under lateral action such as that due to wind and seismic forces, masonry infills significantly affect the mechanical performances of encasing structural systems such as reinforced concrete (RC) frames. Earlier experiments conducted by Stafford Smith (1962, 1967b,a) and Mainstone (1971) indicated that the presence of masonry walls markedly enhanced the in-plane stiffness and ultimate resistance of surrounding frames. Because of low natural period due to increased in-plane stiffness, infilled frames attract high in-plane forces under seismic action. Currently, this effect is not taken into account by designers due to the complexity of analysis and the inherent degradation of the masonry mechanical properties as such composite systems deform. Because of this variability, designers usually rely solely on the frame ability to resist in-plane lateral forces.

According to test results, one can clearly isolate three main phases of load-deformation behaviour from which three distinct mechanical properties can be determined. Before the occurrence of the first major crack, the first stage is characterized by a linear portion of the response curve from which the initial tangent stiffness, K_i, is determined. Generally, occurrence of the first crack coincides with initiation of the second stage which is characterized by a reduced secant stiffness, K_c. The latter has been referred to as the effective stiffness of an infilled frame by other researchers including Benjamin and Williams (1958), Mainstone (1971), Bennett et al. (1996), Tomasevic et al. (1996) and Penelis and Kappos (1997). Although extensively damaged as it progresses towards its ultimate resistance, an infilled frame still exhibits much greater stiffness compared to that of an open frame. Defined as the ratio between the peak force and the corresponding diagonal displacement, K_u, the stiffness at this state is referred to as the residual stiffness of an infilled frame.

Summarized by Moghaddam and Dowling (1987), a number of parameters which affected the stiffness of infilled frames included the aspect ratio and the presence of an opening. Studies conducted by Benjamin and Williams (1958) concluded that an increase in specimen aspect ratio results in marked reduction of infilled frame stiffness. Polyakov (1957) and Coull (1966) reported a reduction up to fifty per cent of in-plane stiffness when infills were constructed with an opening. These studies also concluded that frame rigidity does significantly influence the in-plane stiffness of the tested specimens.

The primary purpose of the present study is to investigate the concurrent effect of the aspect ratio, α, the beam-to-column moment of inertia ratio, β and the effects of openings on the in-plane stiffness of an infilled frame. Results were used to derive empirical formulations which would assist in assessing in-plane stiffness of RC frames infilled with masonry panels.

2 Investigative Technique

2.1 Description of Test Specimens

Forty eight one-third scale models of single story, single bay specimens were fabricated and tested. The specimens were assigned to various series according to the combination of investigated parameters. Parameter values were chosen to cover practical ranges encountered in real buildings so that gathered information would be applicable to actual situations. Test parameters included aspect ratio values of 0.5, 1 and 2, and inertia ratios of 0.2, 1 and 5. To characterize the doorway, an opening coefficient was defined as follows:

$$\eta = 1 - \sqrt{\frac{A_{op}}{A_w}} \qquad (1)$$

where A_{op} and A_w represent the opening and masonry panel areas, respectively. While open and infilled frames yielded opening coefficients of 0 and 1 respectively, specimens with a doorway were characterized by an opening coefficient of 0.6. Overall specimen dimensions depended on their respective aspect and inertia ratios. Table 1 includes the centreline to centreline dimensions of the tested configurations.

2.2 Fabrication

The fabrication process involved three major phases which included the steel reinforcing cage preparation, the concrete pour, and the eventual paneling of designated RC frames. After cutting to length and tieing, the reinforcing bars were placed in the formwork, checked for squareness and spacing before pouring the concrete. Specimens were cast with a microconcrete mix in which a coarse sand replaced the coarse aggregate. Although microconcrete was used to cast forty specimens, four tested by Hobona (1995) were poured with normal concrete. Four additional specimens including S1PL, S2PL, R1PL and R2PL were cast using a lightweight concrete.

Poured in horizontal position, the specimens and related concrete cylinders were demolded after 24 hours, raised in upright position, and moist-cured in the laboratory environment for 7 days. Thereafter, they were left enclosed in plastic burlap for curing until testing at least twenty eight days later. Control specimens were similarly tested.

A professional mason panelled selected test RC frames. Masonry infills were made of solid bricks laid on their edges to yield a panel of 60 mm thick. Two sizes of brick units were used including full scale solid bricks laid on their edges and one-third scale bricks obtained from cutting full scale units (Hobona, 1995). The former method was used extensively while the latter was limited to a few specimens due to the cost involved in the production of these scale units. Type N mortar was used throughout this study.

2.3 Test Setup, Instrumentation, and Testing Procedure

Forty-four specimens were subjected to monotonic in-plane diagonal loading. This general testing procedure has been found to provide a good simulation of the behaviour of infills in frames under in-plane racking force. Although this arrangement has been adopted by numerous investigators including Mainstone (1971), Ma (1983), Samai (1984), and Moghaddam and Dowling (1987), this assumption was validated in a complementary racking test program conducted by Dunham (1996).

Since overall in-plane deformations were of interest, specimen diagonals were instrumented such that their deformations could be continuously monitored by means of linear strain converters (LSC's) as shown in Figure 1. The instruments were connected to a multi-channel data acquisition system for recording purposes. In addition to the frame diagonal displacements, the diagonal load was also continuously recorded. Applied monotonically, the diagonal force was increased in 4.5 kN increments up to ultimate.

At each load increment, the specimen was visually inspected for cracks subsequently reported on a template. As loading progressed, each specimen underwent significant deformations accompanied by extensive damage to both masonry panel and surrounding RC frame. Beyond the peak load, testing was terminated when the deformation and the damage were judged to be extensive.

3 Discussion of Test Results

For each tested specimen, an experimental load vs displacement curve was recorded from which defined stiffnesses were determined. The initial stiffness, K_i, was derived from the initial section of the load displacement curve. K_c and K_u were measured as secant stiffnesses at the occurrence of the first major crack and at ultimate, respectively. To determine how the parameters affected in-plane stiffness of infilled frames, regression analyses were conducted on the experimental results. Subdivided into series according to the combination of investigated variables, the average stiffness of each group is reported in Table 2. For diagonally tested specimens, stiffnesses were based on load horizontal components which were consistent with racking load direction. Due to the symmetry of diagonal testing, results relative to open frames S2B and R2B series were directly derived from tests conducted on S5B and R5B, respectively.

Experimental results indicate that the controlled variables affected the in-plane stiffness of infilled frames at various degrees. Even provided with an opening, infilled frames were stiffer than open frames. The marked effect of masonry panels on in-plane stiffness was modified by either the specimen aspect ratio or the inertia ratio of encasing frame members.

3.1 Initial Tangent Stiffness

As pointed out by Bertero and Brokken (1983), the infills significantly affect the initial stiffness of framed structures. In comparison with open frames, continuous panels increased K_i by a factor varying from 10 to 40 depending on both the specimen aspect ratio and member inertia ratio. As specimens increased in height, flexural behaviour dominated over that of shear and ultimately led to lower initial stiffness. The average initial stiffness of rectangular specimens with an aspect ratio of 2 was reduced by more than fifty percent compared to that of specimens with aspect ratio of 0.5. It was evident that the member flexural stiffness played a role in the stiffness of the structural system. In similar categories frames with stronger beams were stiffer than those with identical member cross sections.

For the initial tangent stiffness, a regression analysis conducted on experimental results of forty-seven specimens indicated that the effect of the investigated variables could be summarized by the following empirical expression with a coefficient of determination, R^2 of 0.97.

$$K_i = e^{\Lambda_1} \qquad (2)$$

where $\Lambda_1 = -0.66\,\alpha + 0.10\,\beta + 4.44\,\eta - 1.22\,\alpha\,\eta$. While η has been defined in Eq. 1, $\alpha = H/L$ and $\beta = I_b/I_c$ represent the specimen aspect ratio and the beam-to-column inertia ratio, respectively.

As expected, specimens with continuous infills exhibited high initial tangential stiffness whose magnitude depended on the aspect ratio. As illustrated in Figure 2, the rate of increase of the initial tangent stiffness was greater for specimens with lower aspect ratio. In general, specimens with stronger beams exhibited higher in-plane rigidity. A unit increase in inertia ratio resulted in more than ten percent increase in lateral tangent stiffness.

3.2 Secant Stiffness at Initial Major Crack

As mentioned previously, the secant stiffness at the occurrence of the first major crack has been referred to as the effective stiffness of the composite system. K_c would therefore be used for the in-plane stiffness in computing the natural frequency and other dynamic properties of infilled frames. Tests conducted by Benjamin and Williams (1958) concluded that an increase in aspect ratio results in reduction of the infilled frame stiffness. These results were later confirmed by numerical experiments conducted by Riddington (1977). This conclusion is consistent with the results of the present study. Specimens with aspect ratio of 0.5 were stiffer than test units with greater aspect ratio. The average stiffness of specimens with a central doorway was increased by a factor ranging from 3 to 6 with respect to that of bare frames. Conducted on thirty-four specimens, all these aspects mentioned above were summarized in a regression model with a coefficient of determination, R^2 of 0.98 as given in Eq. 3.

$$K_c = e^{\Lambda_2} \tag{3}$$

where $\Lambda_2 = -0.69\,\alpha + 0.39\,\beta + 4.63\,\eta - 0.48\,\beta\,\eta$.

Although the investigated variables significantly affected the secant stiffness at the occurrence of the first major crack, the marginal effect of the the presence of an opening depended on the relative flexural rigidity of the encasing frame members. Within the investigated range of the opening coefficient, the rate of increase of K_c for frames with stronger beams was lower than that of infills whose frame members were of identical cross-sections as illustrated in Figure 3. This suggests that infill is more beneficial for frames with weaker beams. As the flexural relative stiffness increased, the surrounding frame provided an additional confinement to the infill which delayed the occurrence of the first crack. This led to the occurrence of the first crack at a greater diagonal displacement than that of corresponding frames with identical members. Therefore, with respect to frames with continuous masonry panels, the stronger the beams, the lower the in-plane secant stiffness.

In addition, the results indicated that the effect of the presence of an opening should be associated with that of the beam-to-column relative stiffness. The reduction of in-plane stiffness due to the presence of a doorway ranged from forty to eighty percent depending on the frame inertia ratio. The highest reduction was recorded mostly from specimens with inertia ratio of 1. A similar range of stiffness reduction has been reported by Coull (1966) and Mallick and Garg (1971). Contrary to what has been reported previously, the present experimental study concluded that the inertia ratio affects the in-plane stiffness of infilled frames. Previous assessments were mainly based on limited test data in which parameters were investigated independently. A unit increase in the aspect ratio resulted in a fifty per cent reduction of the secant stiffness at the first crack.

3.3 Secant Stiffness at Ultimate

Considered as the infill residual stiffness, the secant stiffness, K_u, at ultimate did not appear to depend on the specimen aspect ratio. As summarized by Eq. 4 derived from forty-seven tests, the regression model with R^2 of 0.83 indicated that K_u of depended mostly on the inertia ratio and the opening coefficient.

$$K_u = e^{\Lambda_3} \tag{4}$$

where $\Lambda_3 = 0.12\,\beta + 2.27\,\eta - 0.48\,\beta\,\eta$.

The effect of the presence of an opening in the infill depended on the relative stiffness of the encasing frame. For specimens with continuous infills K_u decreased as the inertia ratio increased as illustrated in Figure 4. Although extensively damaged, at the ultimate these specimens exhibited a residual stiffness up to nine times that of open frames.

4 Conclusions

This experimental investigation revealed how the aspect ratio, the beam-to-column inertia ratio and the opening coefficient affect the in-plane stiffness of RC infilled frames. To characterize the in-plane rigidity, three values of stiffness were defined and referred to three distinct phases of infilled frame behaviour. Investigated properties were the initial tangent stiffness, the secant stiffness as the first major crack, and the secant stiffness at ultimate. Although the aspect ratio did not influence the ultimate stiffness, it significantly affected both K_i and K_c. A unit increase in aspect ratio resulted in fifty percent reduction of the infilled frame stiffness at the first major crack. This is consistent with results reported from other studies. Contrary to what has been reported by others including Moghaddam and Dowling (1987), the inertia ratio in interaction with the opening coefficient was found to have a marked effect on the lateral stiffness K_c and K_u. Despite a ten percent increase in K_i due to a unit increase in inertia ratio, the changes in K_c and K_u depended greatly on β. Regression analyses led to empirical formulations which could be used in the assessment of the stiffness of infilled frames. Although in the present study, specimens were not subjected to vertical loads to simulate forces from upper storeys, the results provide valuable information and analytical tools on the combined effect of investigated variables on the in-plane stiffness of RC infilled frames.

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Table 1: Geometrical Characteristics of the Specimens

Specimen	Height mm	Length mm	Beam b x h	Column b x h	Inertia Ratio $\beta = I_b/I_c$
Square	1000	1000	100 x 100	100 x 100	1
			100 x 170	100 x 100	5
Rectangular	650	1300	100 x 100	100 x 100	1
			100 x 170	100 x 100	5

Table 2: Average Stiffnesses of Tested Specimens

Specimen Series	Aspect Ratio, α	Inertia Ratio, β	η, Opening Coefficient	K_i kN/mm	K_c kN/mm	K_u kN/mm	Number of Specimens
S1B	1	1	0.0	2.18	NA	0.98	4
S1W	1	1	0.6	11	6.3	3.06	3
S1P	1	1	1.0	72.8	56.54	8.89	6
S5B	1	5	0.0	2.4	NA	1.7	3
S5W	1	5	0.6	22	15.02	6.13	3
S5P	1	5	1.0	49	43.3	5.54	4
S2B	1	0.2	0.0	2.4	NA	1.7	3
S2P	1	0.2	1.0	107.2	89.89	20.1	3
R1B	0.5	1	0.0	2.14	NA	1.54	3
R1W	0.5	1	0.6	15.3	10.32	1.2	3
R1P	0.5	1	1.0	87.72	66.1	6.52	3
R5B	0.5	5	0.0	6.27	NA	2.14	3
R5W	0.5	5	0.6	33.86	20.37	1.39	3
R5P	0.5	5	1.0	77.67	38.17	2.49	3
R1PRL	2	1	1.0	35.84	26.92	11.23	2
R2P	2	0.2	1.0	21.62	21.62	8.8	2
R2B	2	0.2	0.0	3.14	NA	1.07	3

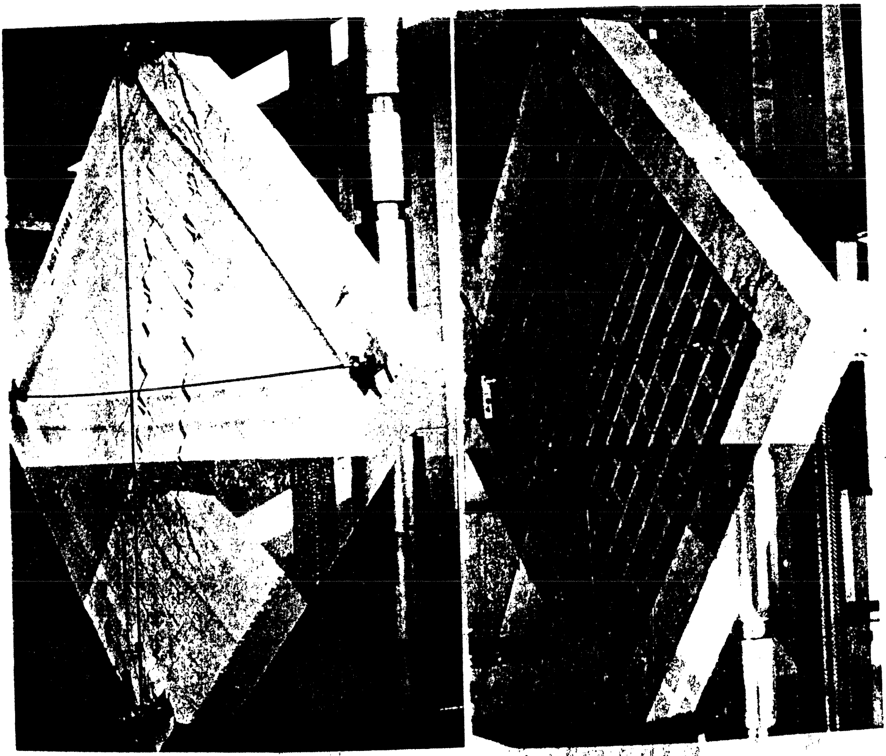
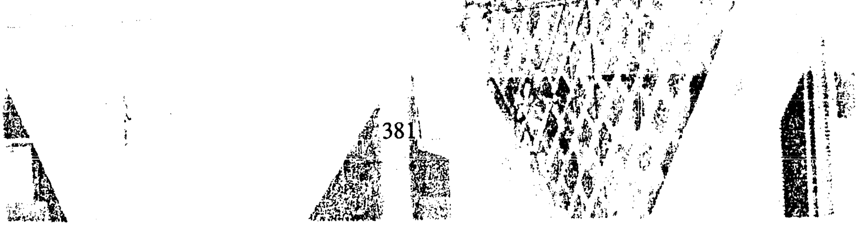
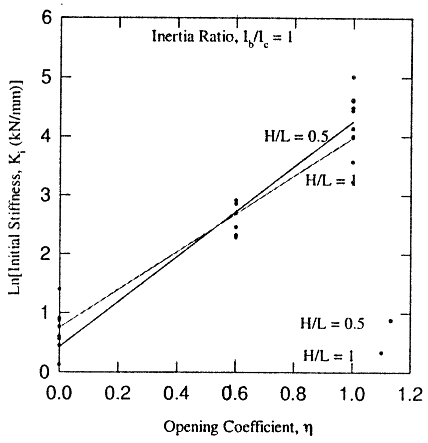
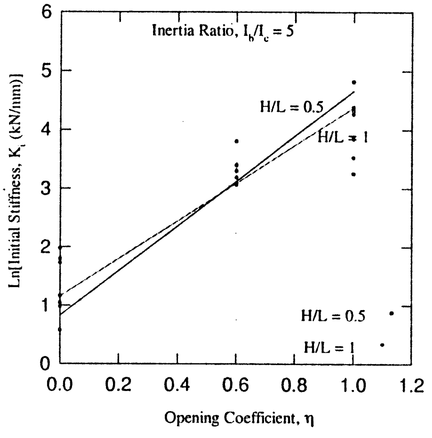


Figure 1: Typical Instrumentation of an Infilled Frame.



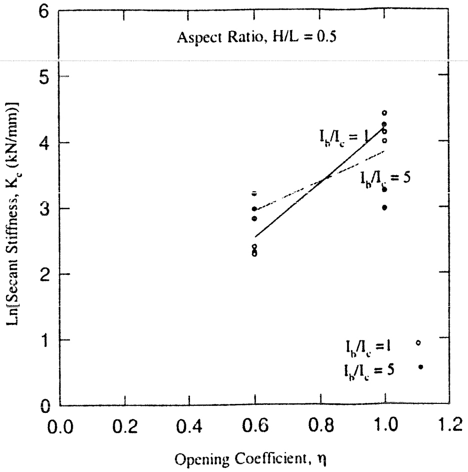


(a) Specimens with $I_b/I_c = 1$

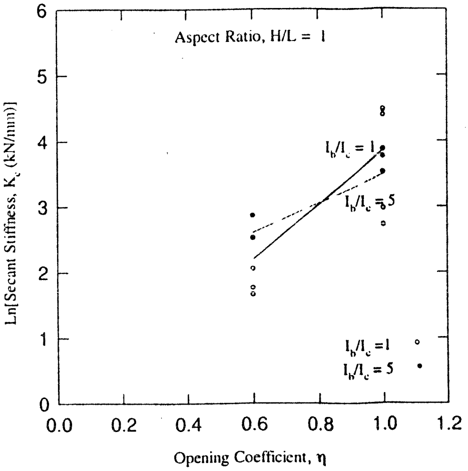


(b) Specimens with $I_b/I_c = 5$

Figure 2: Initial Tangent Stiffness vs Opening Coefficient



(a) Rectangular Specimens



(b) Square Specimens

Figure 3: Secant Stiffness at First Crack vs Opening Coefficient

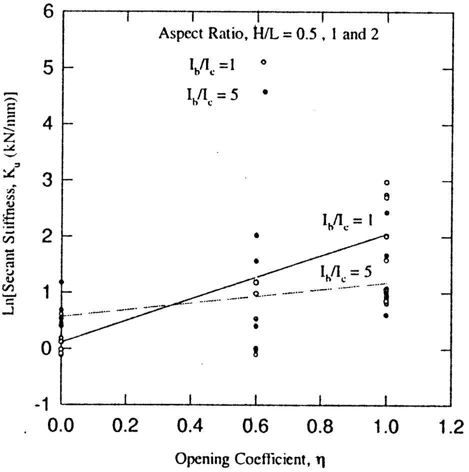


Figure 4: Secant Stiffness at Ultimate, K_u