A PRACTICAL APPROACH FOR THE DESIGN OF MASONRY INFILLED FRAMES

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ABSTRACT

A computerized analytical method wherein masonry infills in frames are replaced with equivalent diagonal springs has been developed. A diagonal load-deformation response for each dissimilar infill in a multi-paneled structure is established using a specially developed finite element program which accounts for panel and frame interaction as well as for various failure modes of the panel and frame. Data defining equivalent diagonal springs for commonly occurring masonry panel dimensions and properties are generated and tabulated for use in standard frame analysis programs. The technique is verified by comparing analytical results with the laboratory results of two 3-storey, 3-bay infilled reinforced concrete frames.

Key words: masonry, infill, frame, steel, concrete, multi-panel, design aid

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INTRODUCTION

Research into the behaviour of masonry infilled panels in framed structures has been documented in various publications over the past five decades. Design guidelines, however, are non-existent in most current codes (Canadian Standards Association 1994a, Masonry Standards Joint Committee 1995). This may be due partly to questions which still exist regarding the applicability of research results to the design of practical infilled frames with dimensions, materials, and construction procedures which generally differ from those used in research programmes. Additionally, a lack of design aids further inhibits the deliberate use of this structural system by design engineers. The study presented herein attempts to resolve these difficulties by providing practical procedures and aids for the design of general multi-storey, multi-bay masonry infilled frames.

While the analytical model described in Dawe et al. (2001) provides a powerful means for evaluating the complex behaviour of masonry infilled frames, the computing resources required for conducting such large-scale analyses for general three-dimensional infilled frames are not widely available. Designers generally require simpler methods that can be processed with commonly available computing facilities. The method developed herein represents a compromise that reduces computing resource requirements and yet is able to reasonably approximate the response of infilled frame structures subjected to lateral in-plane loads. The essence of this procedure consists of replacing each infill panel with a pair of diagonal springs where the assigned load-deformation characteristics of these springs are such that the overall lateral load response of the equivalent infilled frame system can be replicated. It should be noted that the equivalent diagonal springs are active only in compression. The method can be used for analysis and design of general, three-dimensional frames with masonry infill.

DEVELOPMENT OF ANALYTICAL PROCEDURE

Single-storey, single-bay infilled frame

A typical load-deformation curve established by a detailed finite element analysis (Dawe et al. 2001) of a typical single-storey, single-bay infilled frame subjected to horizontal racking load applied at roof level is shown in Figure 1. The initial high strength and stiffness of the system are due to the masonry infill confined within the frame. Alternatively, a compression brace as shown in Figure 2, may be introduced in the frame to achieve the same effect as the infill. For the diagonal brace model to replicate the entire load-deformation response of the actual structure, its load-deformation characteristics must be related to the load-deformation curve for the actual infilled frame (Figure 1). Referring to Figure 3, this relationship can be established as follows:

$$C_d = \frac{H}{Cos\vartheta} \qquad (1)$$

$$\Delta_d = \Delta_h Cos\vartheta - \Delta_v Sin\vartheta \qquad (2)$$

where, C_d is the compression force in the diagonal brace and Δ_d is the corresponding diagonal deformation. H, Δ_h, and Δ_v are the horizontal racking load, and horizontal and vertical displacements at the loaded corner of the infilled frame, respectively. ϑ is the angle of inclination of the frame diagonal measured as shown in Figure 3. Using Eqns. 1 and 2, the entire load-deformation curve of the required diagonal brace can be generated from analytical values of H, Δ_h, and Δ_v using the method described in Dawe et al. (2001). For example, the load-deformation curve of the equivalent diagonal brace for the single-storey, single-bay infilled frame subjected to horizontal racking load applied at roof level is generated and presented in Figure 4. It should be pointed out that the curve of C_d vs. Δ_d gives the relationship of the equivalent diagonal force and deformation of the infilled frame system and therefore includes the rigidity of the surrounding frame. Hinges were introduced to eliminate the lateral resistance of the frame in the simplified diagonal compression brace model shown in Figure2.

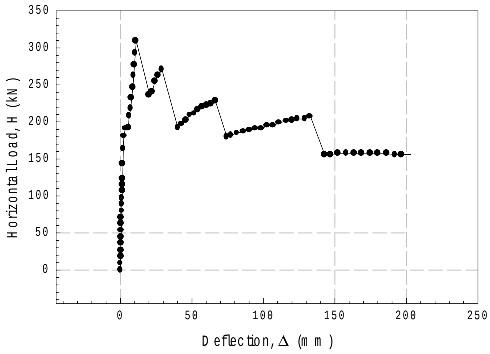


Figure 1. Typical Horizontal Load v. Deflection Curve

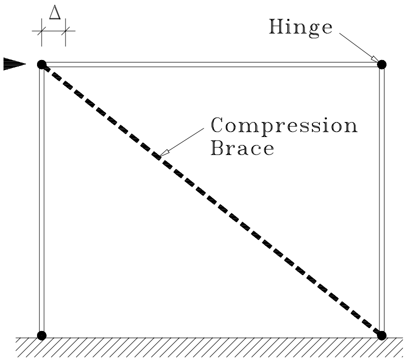


Figure 2. Compression Diagonal Spring Simplified Model

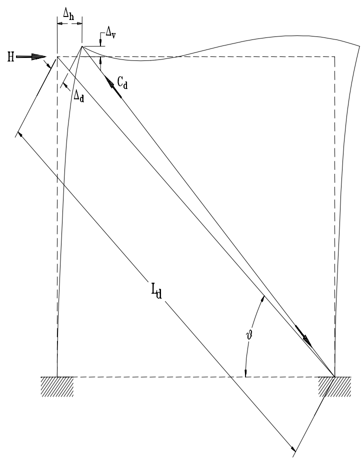


Figure 3. Relationship Between Horizontal and Diagonal Load and Deflection

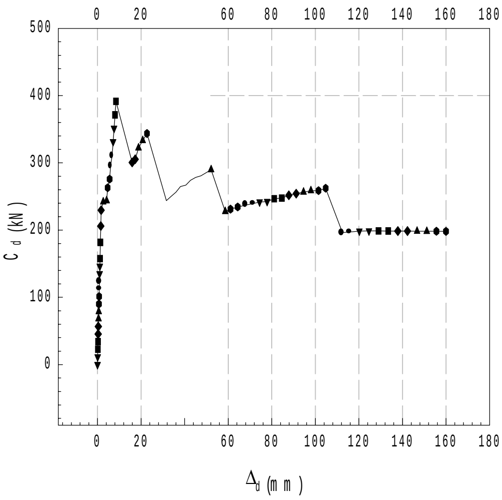


Figure 4. Diagonal Load v. Deflection Response of Equivalent Diagonal Spring

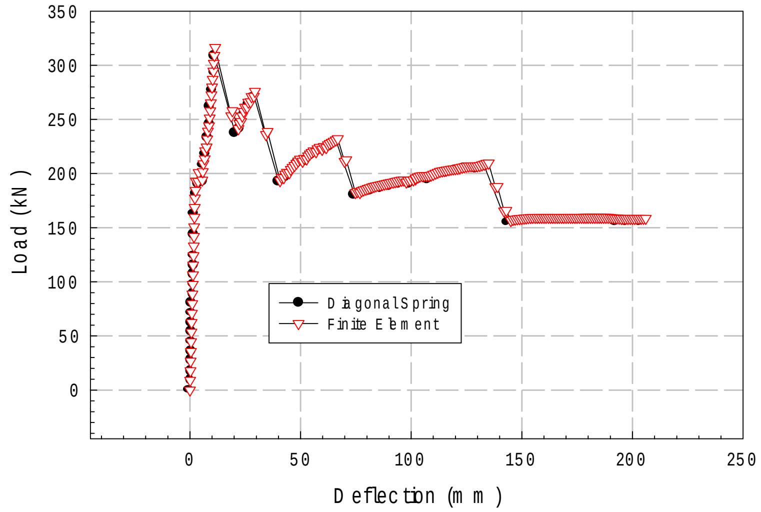


Figure 5. Horizontal Load v. Deflection Response for Single-Bay, Single-Storey

The infilled frame mentioned before was analyzed using a simplified equivalent diagonal brace based on the load-deformation response shown in figure 4. It was also analyzed using the detailed finite element method described by Dawe et al. (2001). The results of both analyses are compared in Figure5. It is evident that the simplified diagonal compression brace model is able to replicate almost identically the results of the more detailed finite element analysis of the structure. Generally, in the analysis of a complex structure, an elaborate and time consuming finite element analysis is required to generate the load-deformation curve of each diagonal brace used. However, for a general three-dimensional frame where identical, or nearly identical infill panels are used to provide lateral resistance, only one such curve, which applies to all panels, needs to be generated. This simplification permits an efficient and cost-effective evaluation of the contribution of the infills in a building. The equivalent diagonal can also be generated for panels with characteristics such as openings, column-to-panel ties, bond beams, and interfacial gaps between panel and frame.

Single-storey, multi-bay infilled frame

The technique described above was extended for the analysis of a single-storey, multi-bay infilled frame system. Figure 6 illustrates a typical single-storey, three-bay infilled frame system under horizontal racking load applied at roof level. Because of the interaction between frame and panels, panel corners alternate between loaded and unloaded conditions, as indicated. Typically, contact between frame and infill is maintained only over a small region near the loaded corners. It is therefore reasonable to assume that Panels A, B and C in Figure 6 behave in a manner similar to that of an individual single-storey, single-bay frame and under this assumption, they contribute equally to the load resistance of the overall frame system. In this example, panels A, B, and C have identical dimensions and material properties. Diagonal members having identical load-deformation responses can therefore replace them.

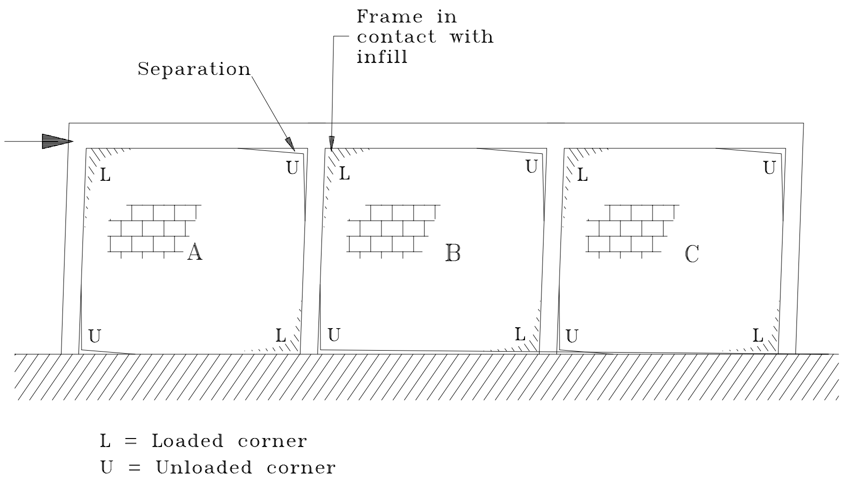
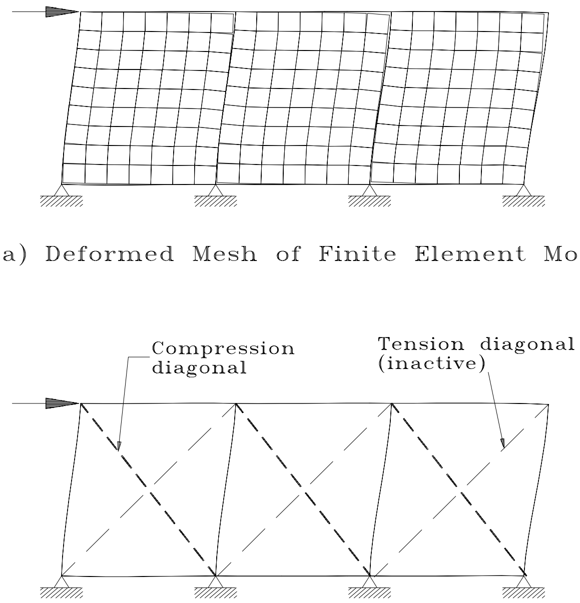


Figure 6 Single-Storey, Three-Bay Infilled

Figure 7(a) shows the computer-generated deformed mesh of a detailed finite element model used to evaluate the behavior of the single-storey, three-bay frame shown in Figure 6. As shown by the deformed mesh, interaction between panels and frame results in contact and separation at loaded and unloaded corners, respectively. A simplified



(a) Deformed Mesh of Finite Element Model

(b) Compression Brace Simplified Model

Figure 7 Analytical Model for One-Storey, Three-Bay Infilled

diagonal spring model of the same structure is shown in Figure 7(b). A graphical comparison of horizontal load-deflection responses for these two models is presented in

Figure 8 and clearly indicates that the simplified diagonal spring model reasonably predicts the strength and stiffness of the single-storey, multi-bay frame up to the peak load and somewhat beyond. The post peak strength, as determined by the simplified spring model, is slightly higher when compared with results of the detailed finite element model analysis of the system. Since, in normal design practice, the primary objective is to ensure that the peak load is not exceeded, the discrepancy in the post-peak region does not seriously compromise the efficacy of the simplified diagonal brace model. Additionally, the economic advantages in time and cost afforded by the simplified model surpass any slight disadvantage of post-peak discrepancies, which are most likely impossible to predict exactly due to the random cracking and deterioration of the masonry infill.

Multi-storey, single-bay infilled frame

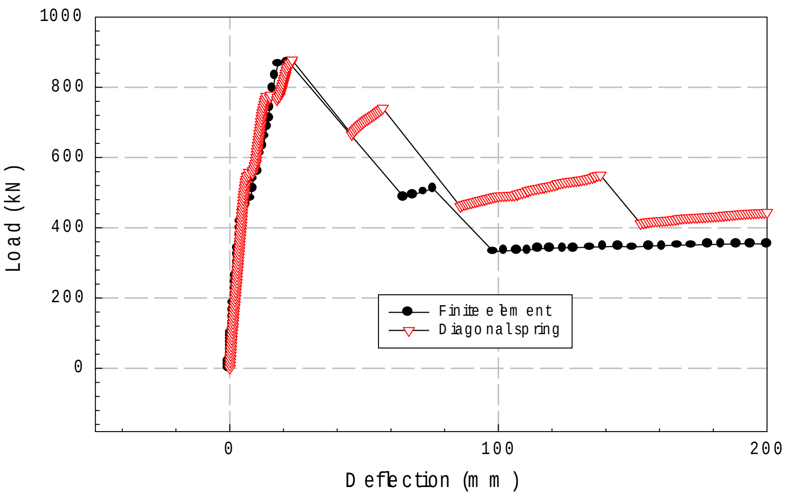


Figure 8. Horizontal Load v. Deflection for One-Storey, Three-Bay Infilled

In a manner similar to a single-storey, single-bay system, each panel of a three-storey, single-bay frame under lateral loading separates from the frame at low load while contact between frame and panel infill is maintained over a small region at the loaded corners. Again, since the loaded corner of one panel is adjacent to the unloaded corner of an adjoining panel, any interaction of adjacent panels in these regions is minimal and therefore may be neglected. Diagonal springs that are generated on the basis of the behavior of a single-storey, single-bay system, are used to replace the panel infills.

A simplified diagonal brace model in this case gives a reasonably satisfactory correlation between the detailed finite element analysis and the simplified model up to the vicinity of the ultimate load. For reasons explained above, exact predictions and precise correlation beyond this point are most likely virtually impossible to attain.

Multi-storey Multi-bay infilled frames

The simplified technique was further extended to include analysis of a multi-storey, multi-bay infilled frame. A three-storey, three-bay frame was used to validate the applicability of this technique. Assuming that the interaction of each panel within its confining frame is negligibly affected by adjacent panels, load-deformation responses were generated for each panel assuming that single panel infilled frame responses could be used to replace them. Both the detailed finite element model and the simplified model are used to obtain the load-deformation responses. Almost identical load-deflection responses for the two models were obtained up to a load of 400 kN. Beyond this load, the finite element model indicated a loss in stiffness due to cracking of infill. The diagonal spring model indicated a similar loss in stiffness but at a higher load level. This discrepancy is very likely due to restrictions imposed by computing resources. A finite element model with a coarser mesh was used to model the entire three-storey, three-bay frame, while the diagonal spring was obtained for a single infill panel using a model with a finer mesh size. The somewhat coarser mesh of the nine-panel finite element model resulted in higher stresses and therefore cracking at a lower load level in this model than in the simplified spring model. The overall correlation of the two methods for this more complex example is felt to be within reasonable limits of acceptability.

Comparison with Experimental Data

Two one-third scale, three-storey, three-bay reinforced concrete frame test specimens, S331 and S335, with brick masonry infill were tested by Dukuze (1995, 1998). The only intentionally varied characteristic between specimens S331 and S335 was the ratio of the beam moment of inertia to the column moment of inertia. For S331, this ratio was 1:1, while for S335 it was 5:1. The simplified analytical model described herein was used to predict the behaviour of both test specimens and was compared with experimental results. A typical specimen with horizontal, in-plane loading is illustrated in Figure 9. Figure 10

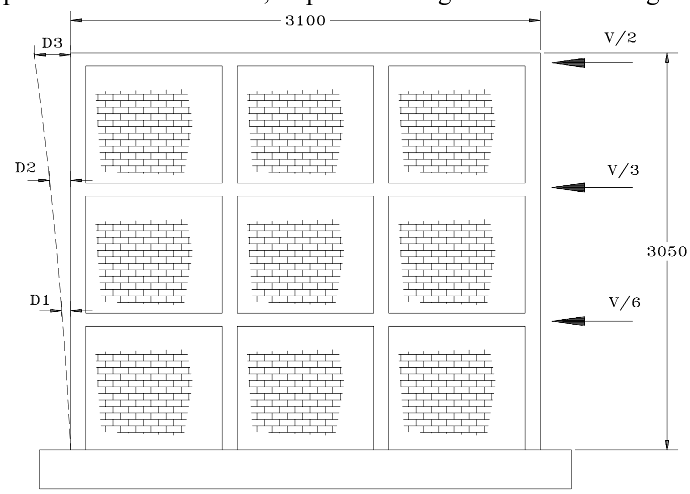


Figure 9 Three-Storey, Three-Bay Infilled Frame

shows load-deformation characteristics for the diagonal springs used to replace infills in the specimens. This procedure is explained in detail in Dawe et al. (2001). In Figure 11, predicted load-deformation behaviour using the simplified diagonal spring model is compared with corresponding experimental results for specimens S331. As is evident in Figure 11(a), (b), and (c), the proposed model closely predicts the ultimate load. The predicted initial stiffness, however, is greater than the apparent value obtained experimentally. The lower stiffness obtained experimentally is not correct because of difficulty encountered during testing. The first three test attempts failed due to various shortcomings in the testing procedure as described by Dukuze (1995). For this reason, some panels had cracked prior to the final test resulting in a softening of the system. The curves shown in Figure 11 are for Specimen S331 the results of testing of the degraded system. In the same manner, a reasonably close predictions of test specimen S335 response is obtained from the initial stage of loading, up to approximately one-half of the total ductile response of the specimen. Beyond this point, extensive cracking and deterioration of the panel and frame combined, caused the efficient manipulation of the numerical calculation to deteriorate, resulting in the discrepancies evident. In spite of these problems, from an overall point of view, the analytical procedure was reasonably successful.

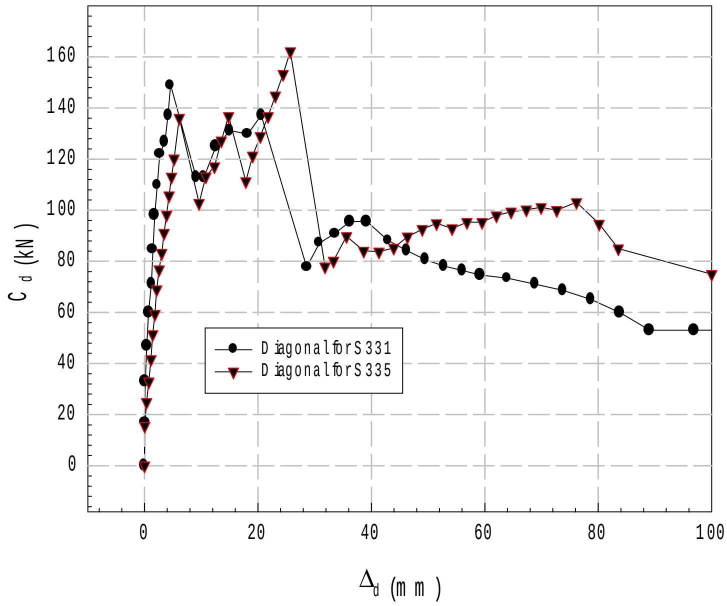
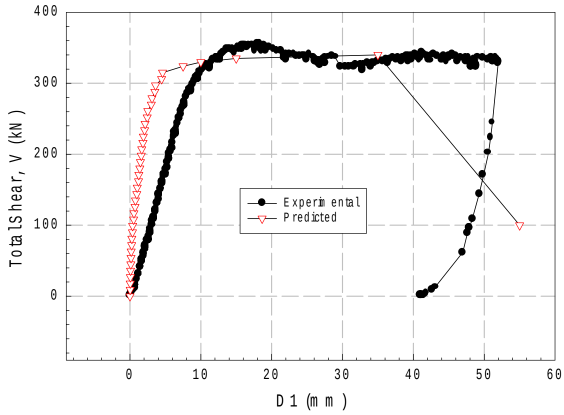
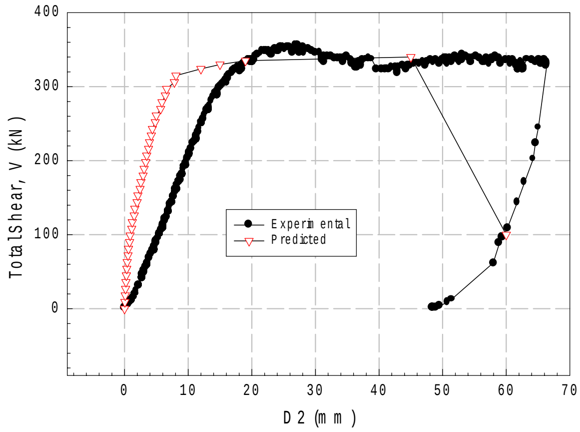


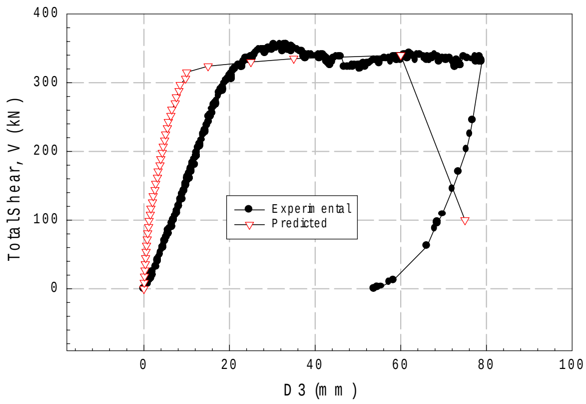
Figure 10 Load v. Deflection Curves of Compression Diagonals Equivalent to Infill



(a) First Floor Level



(b) Second Floor Level



(c) Third Floor Level

Figure 11 Comparison of Load v. Deflection Curves

DESIGN RECOMMENDATIONS

Design Procedures

It is evident that replacing an infill with an equivalent diagonal spring is a practical means of developing a simplified conservative design technique for infilled frame structures (Dawe et al. 2001). A finite element analysis is used to generate load-deformation characteristics of equivalent diagonal springs representing panel infills. The cost effectiveness of this method is significant when there are many identical, or nearly identical, infills in a structure. This technique is also capable of accounting for infills perforated with door or window openings by including the openings in a finite element model used to generate the corresponding load-deformation curve of the equivalent diagonal spring. Other characteristics can be included in the analysis in a similar manner.

Only one analysis is required for each type of infill in a structure to determine the load-deformation curves of equivalent replacement diagonals. A general frame analysis may then be conducted to evaluate the lateral load response of the overall structure (Seah 1998).

General Design Approach

In accordance with limit states design philosophy, the design procedures may be summarized as follows:

1. Determination of load-deformation curves for all dissimilar infills in the structure and replacement of infills with a piece-wise linear approximation of the corresponding response, as shown in Figure 12. (Figure 12 is discussed in more detail below).
2. Analysis of equivalent structure at service load level. Check all forces in equivalent diagonals to ensure these do not exceed the serviceability initial major cracking load limits (point ‘a’ in Figure 12).
3. Analysis of the structure subjected to factored loads to ensure that the force in each diagonal is less than the peak load (point ‘b’ in Figure 12) reduced by an appropriate performance factor. When masonry is used as infilling material, it is recommended that

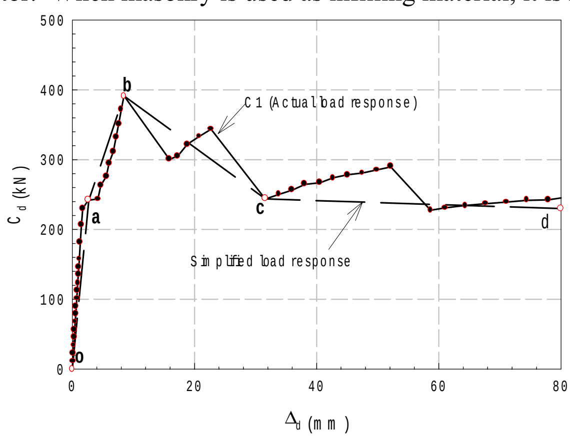


Figure 12. Generation of Simplified Load v. Deflection Response Curve

the performance factor, Φ_m = 0.55, be used, as recommended by CSA S304.1-94 (Canadian Standards Association 1994a).

4. Check axial loads in all columns of the equivalent structure to ensure that the tension or compression forces are within acceptable limits. In determining the load-deformation curves of the equivalent replacement diagonals, the strength and stiffness of the frame are automatically included in the analysis. Failure of the frame, if it occurs, is reflected in the resulting load-deformation curve. Consequently, satisfying the condition in Step 3 above would indicate satisfactory performance of the overall system.

Design Aids

Based on the model developed in this study, finite element analyses of infilled frames were conducted for a practical range of panel dimensions and material properties combined with commonly used steel members. Results of these analyses were examined. A simplified curve of load-deformation response for a typical infilled frame is shown in Figure 12, where C_d is the diagonal load and Δ_d is the corresponding deformation of a panel. The occurrence of an initial primary panel crack along the compression diagonal occurs in the vicinity of ‘a’ and results in a reduction of stiffness of the system. The ultimate load occurs at point ‘b’ where crushing of the infill at high stress areas is imminent. The system stabilizes somewhat at point ‘c’ leading to a quasi-ductile region ‘cd’ of the curve. It is important to include this ductile region, as it may enable alternate load paths, whereby failure of one panel may not lead to collapse of an entire structure.

In some cases, it has been determined that ultimate load is precipitated by, and immediately follows, initial primary cracking. The simplified curve, ‘oacd’, in Figure 13 would apply in such a case. A collection of simplified curves, which were developed for practical purposes, rearranged in the format of diagonal deformation, C_d, versus diagonal deformation, Δ_d , has been generated (Seah 1998). Curves for infills with lengths ranging from 3.5m to 11m and heights ranging from 3.0m to 6.0m were included for associated frames with a wide range of strength and stiffness. Both rigidly connected and simply connected steel frames were considered. All curves are based on plain concrete masonry panel infills fabricated from 200mm thick nominal units with unit strength of 15 MPa and Type S mortar. These curves may also be used for a conservative analysis of frames with reinforced panel infills.

A complete summary of control point coordinates required to define load-deformation response curves suitable for a large range of designs is presented in Seah (1998). Table 1 is an example. These curves are based on infills fabricated from 200 mm concrete masonry units. Correction factors for converting values in these tables to infills fabricated from other units are given in Table 2. In common design practice, a linear elastic analysis is generally performed to distribute member forces throughout a structure. In view of this, the design curves are further simplified by including in the tables K_{UL} and K_{SL}, the secant stiffnesses for the infills (Figure 14). K_{SL} and K_{UL} can be used in a general structural analysis of a building to evaluate the serviceability and ultimate limit states, respectively. In cases where only values of K_{SL} are given, the serviceability limit state of initial primary cracking of a panel infill also corresponds closely to the ultimate capacity of the panel.

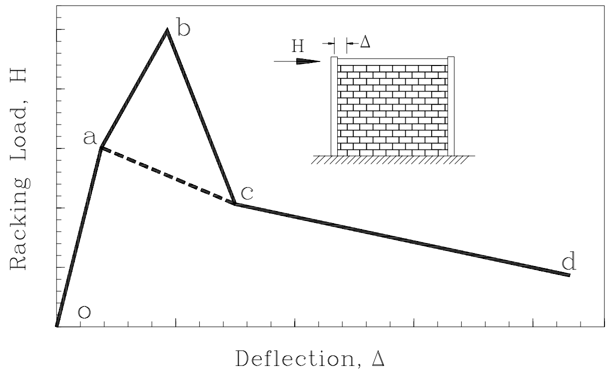


Figure 13 Typical Simplified Load v. Deflection Curve Used for Design

CONCLUSION

The diagonal spring replacement model provides a relatively simple and economical means of predicting the behavior of a general frame structure containing masonry panel infills. Since the load-deformation response of an equivalent diagonal can be generated analytically, this technique can be readily extended to include infilled panels with door and window openings.

The method can also be used for panels where an isolation gap exists between the panel and underside of a roof beam. Generally, the extent of the advantage of this technique is proportional to the number of identical infilled panels in a structure, since a more elaborate, time-consuming finite element analysis is required to determine the load-deformation behavior for each of the dissimilar panels. In many cases, however, it may be possible to replace slightly dissimilar panels with a conservative, equivalent diagonal spring, thus gaining additional economy for small sacrifices in over-design. Comparisons of analytical results show that the diagonal spring model can be used for multi-storey, multi-bay frames.

The agreement between analytical results and test data further validates the procedure presented in this study. The simplified technique also affords an economical procedure for multiple load cases, even for buildings with dissimilar panels.

ACKNOWLEDGEMENT

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Table 1: Definition of Simplified Design Curves: Infill Width = 3.5 to 5.0 m, Height = 3.0 to 4.0 m

3.0 m ≤ Panel height, h_i ≤ 4.0 m   3.5 m ≤ Panel width, w_i < 5.0 m

Frame	Coordinates of Control Points[1]								Stiffness	
	a		b		c		d[2]		K_{SL}	K_{UL}
	Δ_d (mm)	C_d (kN)	Δ_d (mm)	C_d (kN)	Δ_d (mm)	C_d (kN)	Δ_d (mm)	C_d (kN)	(kN/mm)	(kN/mm)
1a	7	245	30	350	50	150	100	130	35.0	11.7
1b	7	200			21	50	60	0	28.6	
2a	7	260	30	360	50	150	100	130	37.1	12.0
2b	7	200			21	50	60	0	28.6	
3a	7	270	30	360	50	150	100	130	38.6	12.0
3b	7	200			21	50	60	0	28.6	
4a	7	245	30	370	50	175	100	150	35.0	12.3
4b	7	240			21	60	60	0	34.3	
5a	8	380	30	750	55	300	100	300	47.5	25.0
5b	7	250			21	62	60	0	35.7	
6a	8	600	25	1150	45	900	100	850	75.0	46.0
6b	7	250			21	62	60	0	35.7	
7a	6	250	30	430	45	175	100	150	41.7	14.3
7b	7	250			21	62	60	0	35.7	
8a	8	380	30	800	53	400	100	390	47.5	26.7
8b	8	250			24	62	60	0	31.3	
9a	12	1000	30	1450	40	1350	100	1300	83.3	48.3
9b	8	250			24	62	60	0	31.3	

[1]Based on infills fabricated from 200 mm CMU. Multiply the ordinates C_d by the correction factors of Table 2 for infills of other nominal dimensions.
[2]Deflection limits are conservatively set at 100 mm for moment resisting frames (eg. 4a) and 60 mm for hinged frames (eg. 4b).

Table 2 : Unit Size Correction Factor

Nominal Unit Thickness (mm)	Correction Factor χ_{C_d}
150	0.80
200	1.00
250	1.08
300	1.15

Table 3: Frame Properties - Minimum Requirements

	Member Properties									
	Column					Beam				
	Stiffness		Strength[1]			Stiffness		Strength[1]		
	AE	EI	M_p	P_p	V_p	AE	EI	M_p	P_p	V_p
Frame	$x10^8$ N	$x10^{12}$ N-mm^2	kN-m	kN	kN	$x10^8$ N	$x10^{12}$ N-mm^2	kN-m	kN	kN
1a	5.0	1.0	30	750	150	5.0	4.0	60	500	120
1b	Pin connected frame, same frame properties as above									
2a	5.0	1.0	30	750	150	15.0	60.0	450	2500	700
2b	Pin connected frame, same frame properties as above									
3a	5.0	1.0	30	750	150	60.0	400.0	2000	8000	2000
3b	Pin connected frame, same frame properties as above									
4a	20.0	50.0	500	4000	650	5.0	4.0	60	500	120
4b	Pin connected frame, same frame properties as above									
5a	20.0	50.0	500	4000	650	15.0	60.0	450	2500	700
5b	Pin connected frame, same frame properties as above									
6a	20.0	50.0	500	4000	650	60.0	400.0	2000	8000	2000
6b	Pin connected frame, same frame properties as above									
7a	40.0	80.0	800	6000	1000	5.0	4.0	60	500	120
7b	Pin connected frame, same frame properties as above									
8a	40.0	80.0	800	6000	1000	15.0	60.0	450	2500	700
8b	Pin connected frame, same frame properties as above									
9a	40.0	80.0	800	6000	1000	60.0	400.0	2000	8000	2000
9b	Pin connected frame, same frame properties as above									

Notes:

1. M_p, P_p, and V_p are the plastic moment, axial, and shear capacity of a frame member, respectively.

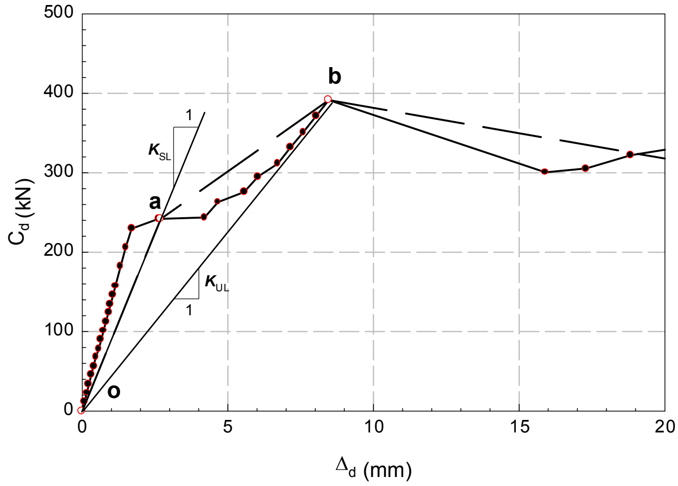

Figure 14. Secant Stiffness for Serviceability and Ultimate Limit States Analysis

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