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Development of Stiffness Reduction Factors for Modelling of Infilled Frames, Case of Varying Configuration of Opening Size

T.C. Nwofor[1] and M.E. Ephraim[2]

[1]Department of Civil Engineering, University of Port Harcourt, P.M.B 5323 Port Harcourt, Rivers State, Nigeria

[2]Department of Civil Engineering, Rivers State University, P.M.B.5080, Port Harcourt, Rivers State, Nigeria

Abstract: **This work presents an assessment of the behavior of infilled frames with different configurations of openings under lateral load. It is now widely recognized that masonry infill panels, used in reinforced concrete (RC) frame structures, significantly enhance both the stiffness and the strength of the surrounding frame but most designs do not consider the shear strength response of the walls and the contribution of the infill panel openings in the reduction of the shear strength of the infill especially in critical cases of dynamic load. Their contribution is often not taken into account because of the lack of knowledge of the composite behavior of the surrounding frame and the infill panel. Currently, Seismic Design Guidelines such as (EC8 – Part 3, FEMA – 440, ASCE 41-06) contain provisions for the calculation of the stiffness of solid infilled frames mainly by modeling infill walls as "diagonal struts." However, such provisions are not provided for infilled frames with different configurations and sizes of openings. A finite element program that utilized the constant strain plane rectangular element for the analysis was developed and used to model one-storey one-bay reinforced Concrete infill frame with different configurations and size of opening ranging from 0 to100% and the performance of reinforced concrete frames under lateral loading were observed. The values obtained for deflection (Δ) against applied lateral force was obtained and used to calculate the shear stiffness (K) and hence the stiffness reduction factors (λ) for varying configurations and size of openings. The results were validated by modeling the same set of structural models with STAAD.ProV8i, which is standard commercial software for FE analysis. Results from this work showed that the developed FE based program compared favorably with the results from STAAD.ProV8i program. The basic specifics drawn from the results is that the estimated stiffness reduction factors to account for varying configurations and sizes of opening vary from a value of 1.0 for the complete rigid frame (β = 0) to a value of about 0.45 for the bare frame (β = 1.0). Hence three reasonable relationships relating the stiffness reduction factor (λ) and the solidity ratio (β) were obtained in the form,** $\lambda = 0.377\beta^{-0.17}$, $\lambda = 0.452\beta^{-0.14}$, $\lambda = 0.502\beta^{-0.12}$

1. INTRODUCTION

Masonry is best used as infill material in load-bearing walls in ordinary constructions and in reinforced concrete frames of high-rise structures. Modern day construction of medium and high-rise buildings require that they be constructed as frame structures because of economy and ease of construction. The reinforced concrete (RC) frame members are infilled with concrete masonry units, blocks, bricks, cast-in-place concrete or wood [1]. Most designers of reinforced concrete (RC) frames usually ignore the beneficial or adverse effects of incorporating infill walls within RC frame structures, hence not much attention is paid to the significance of incorporating infill walls to the shear resistance of the frame structures [2-5]. Routinely, most structural members in a building are designed for i.e. columns, beams, footings etc, while ignoring the presence of masonry units within the framing members of the structure. With the development in research in RC concrete structures subjected to intense lateral load analysis, there ascended a new debate on the performance of the incorporation of these masonry units in the frame members. Research conducted in recent times has proved that masonry units which act as infill material influences the performance levels of the overall building frame [6-15]. Effort has been made in the past to develop analytical models that realistically capture or reproduce the behavior of experimentally tested masonry-infilled RC frames due to many difficult and tedious nature of experimental testing. Analytical finite element methods were subsequently developed but because of the cost of acquiring standard FE software programs, simplified analytical macro-models in form of diagonal strut models used to replace the infill panels that leads to the analysis of the structure as a skeletal model frame has been developed by different researchers who have proposed different versions of strut models ranging from one to multiple diagonal strut models [16-20]. The models developed so far have in rare cases captured the opening in the infill panels and even when they have done so, they varying configuration of opening sizes have not been considered.

This paper intends to investigate the effects of openings at various locations under a lateral load by developing very structured program software that will account for the effect of the opening locations and sizes and subsequently obtain stiffness reduction factors for equivalent strut modeling of infilled frames.

2. THEORETICAL METHOD

The basic method for this research was as follows:

i. Determination of a suitable finite element procedure for a composite structure such as the infilled frame.

ii. Development of a reliable program code for FE modeling of a typical single -bay single-storey brick masonry infilled reinforced concrete frame with varying configuration and size of openings.

iii. Validation of the developed program code with STAAD.Pro V8i which is a standard commercial software.

iv. Extraction of maximum deflections from the output of the developed program.

v. Estimation of shear stiffness and hence the corresponding stiffness reduction factors.

vi. Deducing basic mathematical relationships between the basic variables such as the opening ratio (β), shear stiffness (K) and the stiffness reduction factor (λ).

2.1 Derivation of the Rectangular Element Stiffness Matrix for FE Modeling

The derivation of the stiffness characteristics for a rectangular element in plane stress and plain strain are well developed [21-22] and presented here is a general overview of the approach outlining the seven basic steps below.

Let the rectangular element have sides of lengths *a* and *b*, and a thickness *t* and a node numbering system as shown in Figure 1. Figure 2, shows the eight unknown displacements and Figure 3, shows the corresponding nodal forces. Using matrix notation, the displacements at node 1 may then be written as:

$$\{\delta_1\} = \begin{Bmatrix} u_1 \\ v_1 \end{Bmatrix} \qquad (1)$$

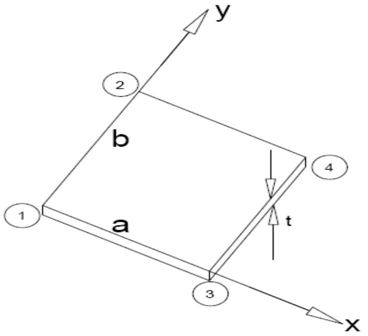

Figure 1: Element Dimension and Nodal Displacement

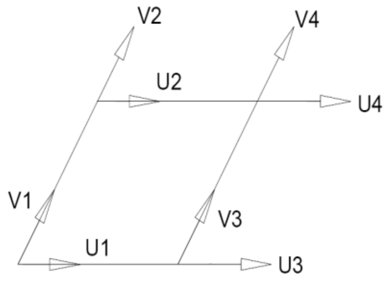

Figure 2: Nodal displacement

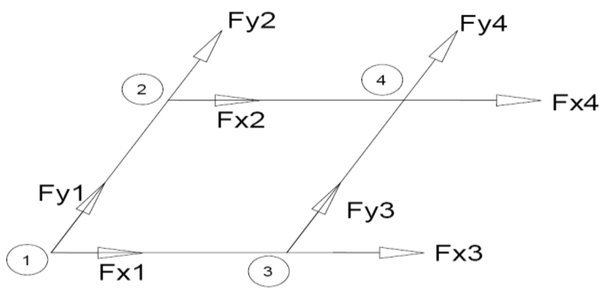

Figure 3: Nodal Forces

The forces at node 1 may be written as

$$\{F_1\} = \begin{Bmatrix} F_{x1} \\ F_{y1} \end{Bmatrix} \tag{2}$$

Each of these vectors contains eight terms so that the elements stiffness matrix $[K^e]$ is now an 8x8 matrix, with a governing equation in the form

$$\{F^e\} = [K^e]\{\delta^e\} \tag{3}$$

In a plane elasticity problem the state of displacement at any point (x, y) within the element is represented by two suitable functions as given in equations 4 and 5.

$$u = \alpha_1 + \alpha_2 x + \alpha_3 y + \alpha_4 xy \tag{4}$$

$$v = \alpha_5 + \alpha_6 x + \alpha_7 y + \alpha_8 xy \tag{5}$$

Where $\alpha_1 - \alpha_8$ represents displacement function constant.

This summarized in equation 6 as

$$\{d(x, y)\} = [f(x, y)]\ \{\alpha\} \tag{6}$$

The State of Displacement $\{d(x, y)\}$ at any point within the element in terms of nodal displacements $\{d^e\}$ can be summarized as

$$\{d(x, y)\} = [f(x, y)]\ [A]^{-1}\ \{d^e\} \tag{7}$$

The strains $\{\varepsilon(x, y)\}$ at any point due to displacements $\{d(x, y)\}$ and hence to nodal displacements $\{d^e\}$ at any point in a plane elasticity element is summarized as

$$\{\varepsilon(x, y)\} = [B]\{d^e\} \tag{8}$$

$$\text{where} \quad [B] = [C][A]^{-1} \tag{9}$$

Matrix *B*, *C* and A contain constant dimensional values of the element considered.

The internal stresses $\{\sigma(x, y)\}$ are related to strains $\{\varepsilon(x, y)\}$ and to nodal displacements $\{d^e\}$ through Equation 10, where matrix D captures the mechanical properties of the elememt material.

$$\{\sigma(x, y)\} = [D][B]\{d^e\} \tag{10}$$

The internal stresses $\{\sigma(x, y)\}$ are replaced with statically equivalent nodal forces $\{F^e\}$ which related to the nodal displacements $\{d^e\}$ and hence obtain element stiffness matrix K^e

The general equation that results from this step is summarized as,

$$\{Fe\} = [\int [B]^T [D][B]\ d(\text{vol})]\ \{d^e\} \tag{11}$$

Where the $[B]$ and $[D]$ as previously defined, matrix K^e from equation 3 can be evaluated as follows,

$$[K^e] = \int [B]^T [D][B]\ d\ (\text{vol}) \tag{12}$$

For an element of constant thickness (t) Equation 12 becomes

$$[K^e] = t \iint [B]^T [D][B]\ dx\ dy \tag{13}$$

The product $[B]^T[D][B]$ has to be integrated over the area of element. The calculation of $[K^e]$ is thus considerably more complicated but still only involves standard matrix procedures. In most cases the final value of the $[K^e]$ matrix would be obtained from computerization which is the basics of most program codes.

2.2 Computer Program Algorithm

A computer program for two dimensional finite element analyses in visual basic developed by the author is used in the implementation of the finite element model. The computer program is divided into two parts. The first part consists of routines for the control numbers and data input modules. The second part consists of routines for tabulated output of nodal displacements and element stresses. The basic steps to obtain the rectangular element stiffness matrix K^e and stress matrix [H] has been discussed in the previous section. This will involve voluminous numerical work; hence these processes were well built up in the program subroutines to take care of the overall analysis. The input data consists of specifying the following:

i. Geometry of the idealized RC. Structure
ii. Its mechanical properties
iii. The loading condition
iv. The support conditions
v. The data also include certain control numbers that would help the efficiency of the program such as the total number of nodes and elements. The infill frame element size of 400x500mm is used for the model.

The basic requirement of the computer program necessary for the complete solution of a problem by the finite element method involves using the input data which describes fully the idealized structure and its loading and in turn produces output consisting of tabulated nodal displacements.

2.3 Validation of the Developed Model

The input data used for the developed FE model was also used for analysis carried out by STAAD. Pro V8i software for the validation of the developed model. Different models of the RC frame were developed and the opening configurations and sizes were varied with a lateral constant load of 50KN applied to the frame as follows.

i. Opening above the compressed diagonal – ACDS (10 - 90% opening, 9 models)
ii. Opening below the compressed diagonal - BCDS (10 - 90% opening, 9 models)
iii. Opening on the compressed diagonal - OCDS (10 – 90%, 9 models)
iv. A bare and rigid frame (one model each)

2.4 Input Data

The basic input data for the developed program and STAAD.Pro software is as follows,

General model information

Type of structure	Single storey single bay frame
Number of storeys	1
Height of building	4m
Infill material	Brick

Section properties

Wall thickness	225mm
Column Sizes	300 x 500mm
Beam Sizes	300 x 500mm

Material properties

Elastic Modulus E_m	4.4×10^6 kN/m^2
Elastic Modulus E_f	2.9×10^7 kN/m^2
Poisson's ratio of masonry	0.22
Poisson's ratio of Concrete	0.20

Primary loading

Lateral load	50kN

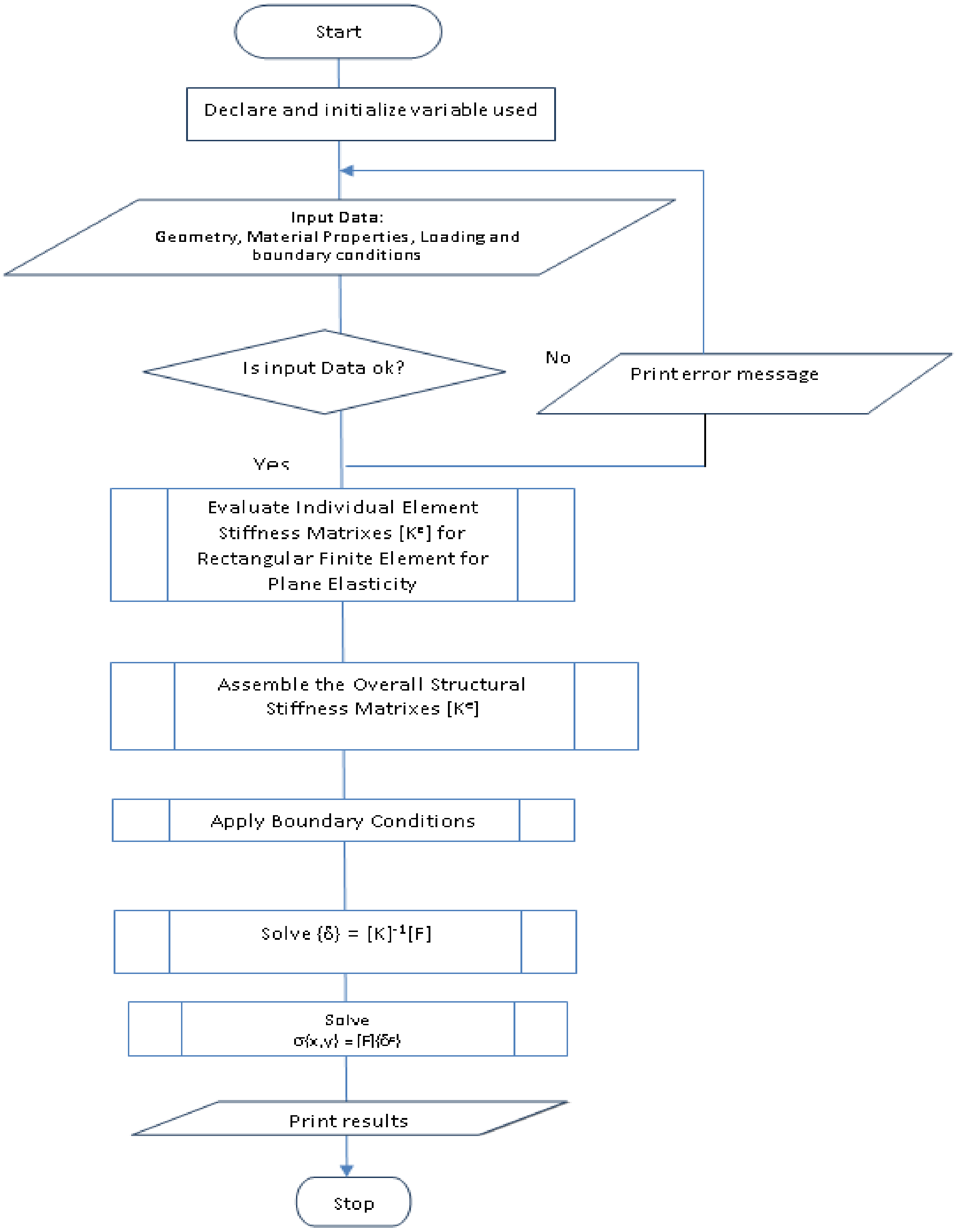

Figure 3.1 -Computer program Flow Chart Diagram for FE Model

2.5 Implementation of the Procedure

A typical representation of a single-bay single-storey masonry infilled RC frame under lateral static load is subjected to analysis using the FE model developed and STAAD.ProV8i software is shown in Figures 4 to 8. A total of 29 structural models consisting of a complete bare frame (100% opening ratio) to infilled frames (with varying opening configurations ranging from 10%-90%) and a complete rigid frame (0% opening ratio) are considered and identified as; ACDS10, ACDS20, ACDS30, ACDS40, ACDS50, ACDS60, ACDS70, ACDS80 and ACDS90. BCDS10, BCDS20, BCDS30, BCDS40, BCDS50, BCDS60, BCDS70, BCDS80 and BCDS90. OCDS10, OCDS20, OCDS30, OCDS40, OCDS50, OCDS60, OCDS70, OCDS80 and OCDS90.

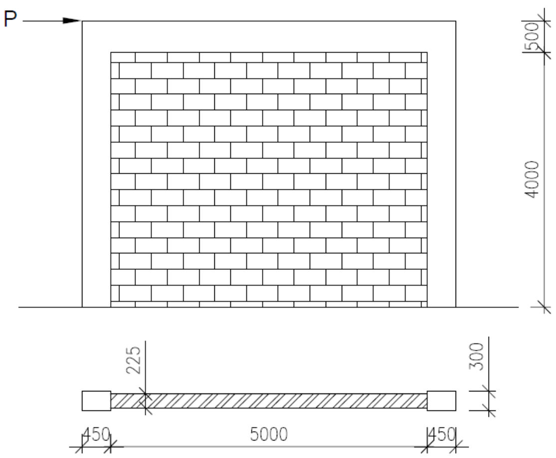

Figure 4: Rigid Infill Frame Structure

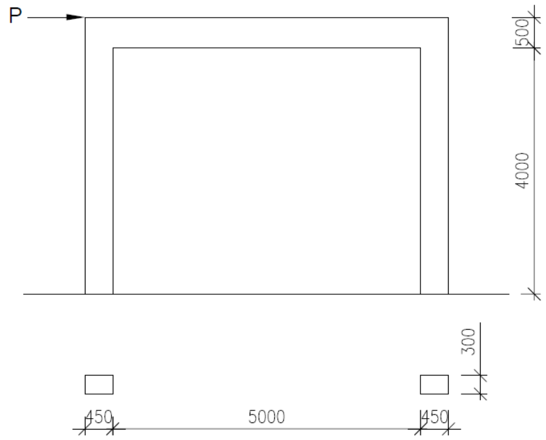

Figure 5: Bare Frame Structure

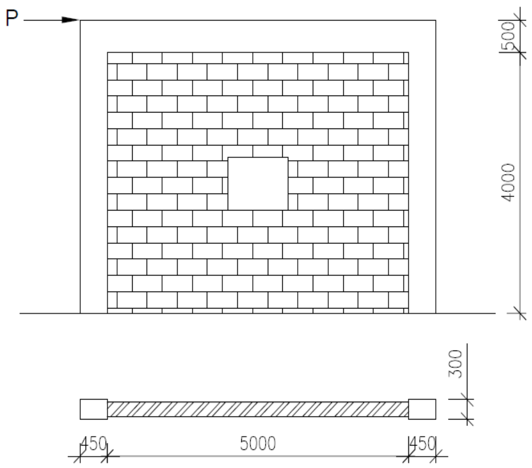

Figure 6: Opening at Centre

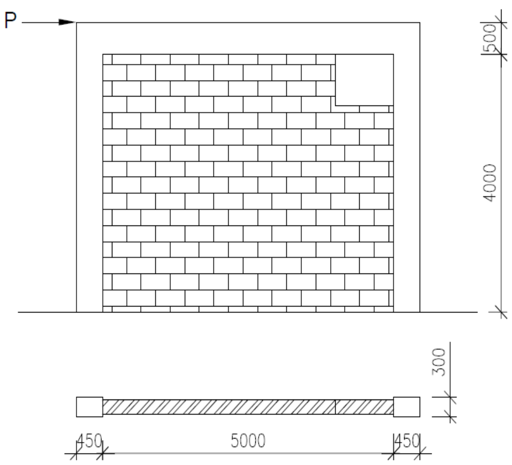

Figure 7: Opening above Compressed Diagonal

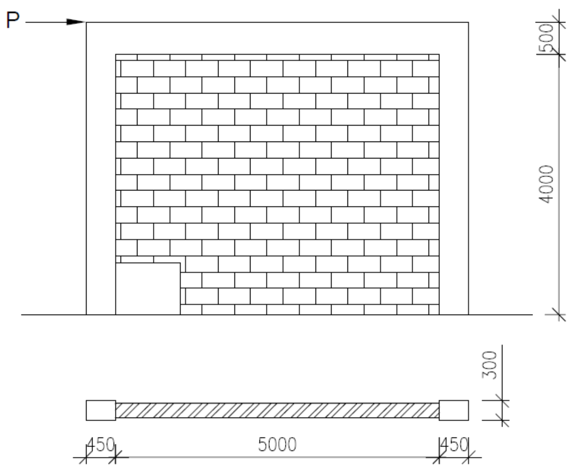

Figure 8: Opening below Compressed Diagonal

The rectangular mesh structure ready for finite element analysis is shown in Figure 9. The FE model requires knowledge of basic mechanical properties of brick components. The elastic properties of bricks are given in Table 1, and was obtained by [20, 23].

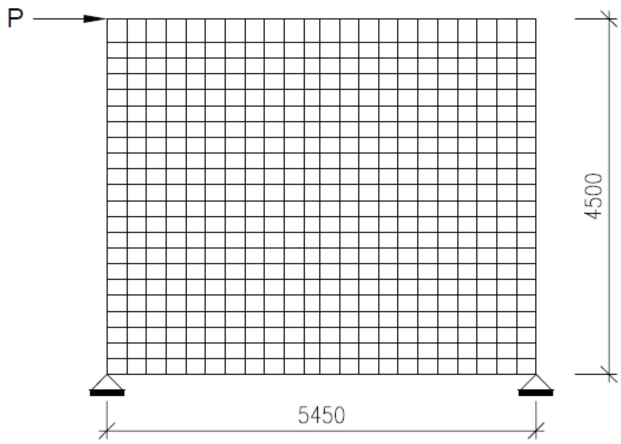

Figure 9: Typical Constant Strain Rectangular Elements Idealization of Structure, ready for FE Analysis.

Table 1:Mechanical Properties of Materials

Material	Modulus of elasticity		Poisson's ratio	
	E_x (KN/ m^2)	E_y (KN/m^2)	V_{xy}	V_{yx}
Concrete	2.9 X 10^7	2.9 X 10^7	0.2	0.2
Masonry	4.4 X 10^6	7.41 X 0^6	0.22	0.33

Note that the infill panel is considered homogenous, hence equivalent modulus of elasticity and poisson's ratio is obtained in two orthogonal directions. The basic physical property for the analysis is the thickness of the panel and for this research, brick unit with a thickness of 225mm was considered.

3. RESULTS & DISCUSSION OF RESULTS

The summary of the full result output from the analysis of the infilled frame carried out by the developed program are presented in Table 2.

The basic Equations and discriptions of the terms used in the Table are as follows;

β = Opening ratio (ratio of opening area to area of infill panel)

Δ = Deflection of Infilled Frame

K = Stiffness of Infilled Frame

F = Force = 50KN = kΔ

K = Stiffness = $\frac{F}{\Delta}$

λ = Stiffness reduction factor (the ratio stiffness of a particular infill frame to stiffness of the rigid frame)

3.1 Deflection on the Sway Frame

The computed values of deflections, shear stiffness and stiffness reduction factors are displayed in the Table below. It was observed that the lateral displacement under a constant lateral force of 50kN increase generally for the three cases from model with a solidity ratio of zero (rigid infilled frame) to that with a solidity ratio of 1.0 (100% opening, Bare frame) from an average value of 1.03mm to about 2.58mm reflecting about 60% increase which is somewhat similar to previous results obtained by Galatin et al., Nwofor and Chinwah, Ephraim and Nwofor [5, 20, 23].

Table 2: Computed Deflection, Stiffness and Stiffness Reduction Factor of Structural Models.

Opening ratio (β)	Model	Deflections (mm) at 50kN Load Application			Stiffness of Infilled Frame (K) (kN/mm)			Stiffness Reduction Factor (λ)		
		Δ1 Central Opening	Δ2 Opening above compressed diagonal	Δ3 Opening below compressed diagonal	K_1 Central Opening	K_2 Opening above compressed diagonal	K_3 Opening below compressed diagonal	λ1 Central Opening	λ2 Opening above compressed diagonal	λ3 Opening below compressed diagonal
0	Developed FEM	1.03	1.03	1.03	48.54	48.54	48.54	1.00	1.00	1.00
	Staad Pro V8i	1.11	1.11	1.11	45.05	45.05	45.05	1.00	1.00	1.00
	% diff.	7.77	7.77	7.77						
0.1	Developed FEM	1.07	0.91	0.80	46.73	54.98	62.31	0.96	1.13	1.28
	Staad Pro V8i	1.06	0.90	0.80	47.17	55.49	62.89	1.05	1.23	1.40
	% diff.	0.93	0.93	0.93						
0.2	Developed FEM	1.79	1.52	1.40	27.93	32.86	35.81	0.60	0.60	0.57
	Staad Pro V8i	1.75	1.49	1.37	28.57	33.61	36.63	0.63	0.75	0.81
	% diff.	2.23	2.23	2.23						
0.3	Developed FEM	1.93	1.64	1.54	25.91	30.48	32.38	0.53	0.63	0.67
	Staad Pro V8i	1.89	1.61	1.51	26.46	31.12	33.07	0.59	0.69	0.73
	% diff.	2.07	2.07	2.07						
0.4	Developed FEM	2.45	2.08	1.84	20.41	24.01	27.21	0.42	0.49	0.56
	Staad Pro V8i	2.23	1.90	1.67	22.42	26.38	29.90	0.50	0.59	0.66
	% diff.	8.98	8.98	8.98						
0.5	Developed FEM	2.71	2.30	2.06	18.45	21.71	24.28	0.38	0.45	0.50
	Staad Pro V8i	2.65	2.25	2.04	18.87	22.20	24.50	0.42	0.49	0.54
	% diff.	2.21	2.21	0.93						
0.6	Developed FEM	2.73	2.29	2.07	18.32	21.80	24.10	0.38	0.45	0.50
	Staad Pro V8i	2.41	2.00	1.83	20.75	25.00	27.30	0.46	0.55	0.61
	% diff.	11.72	12.77	11.72						
0.7	Developed FEM	2.79	2.32	2.06	17.92	21.59	24.22	0.37	0.44	0.50
	Staad Pro V8i	2.50	2.08	1.85	20.00	24.10	27.03	0.44	0.53	0.60
	% diff.	10.39	10.39	10.39						
0.8	Developed FEM	2.81	2.42	2.16	17.79	20.69	23.11	0.37	0.43	0.48
	Staad Pro V8i	2.79	2.40	2.15	17.92	20.84	23.27	0.40	0.46	0.52
	% diff.	0.71	0.71	0.71						
0.9	Developed FEM	2.82	2.38	2.12	17.73	20.98	23.64	0.37	0.43	0.49
	Staad Pro V8i	2.80	2.41	2.10	17.86	20.76	23.81	0.40	0.46	0.53
	% diff.	0.71	-1.05	0.71						
1.0	Developed FEM	2.98	2.50	2.26	16.78	19.97	22.08	0.35	0.41	0.45
	Staad Pro V8i	2.95	2.48	2.18	16.95	20.18	22.90	0.38	0.45	0.51
	% diff.	1.01	1.01	3.61						

It was also noticed from Table 2 and the plot of deflection against solidity ratio in Figures 10 and 11 that the stiffness of the portal frames with central opening significantly reduced compared to other cases as a difference of about 20% was noticed in corresponding deflections when we compare the three cases. This indicates the significance of the compressed diagonal area in the stability of sway infilled RC frames.

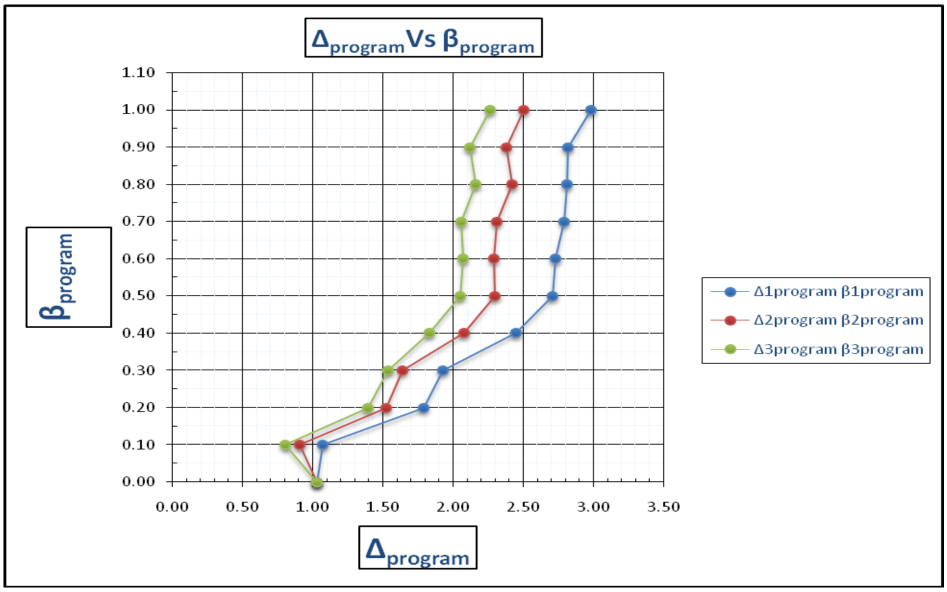

Figure 10: Deflection of RC Frame under Study for Various Opening Configurations
(Values from developed program)

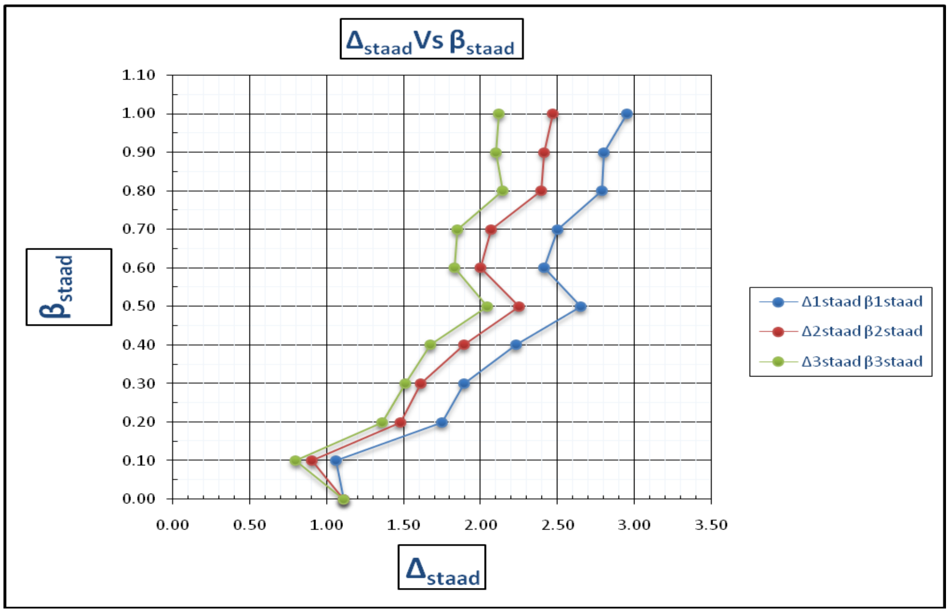

Figure 11: Deflection of RC Frame under Study for Various Opening Configurations
(Values from STAAD. ProV8i program)

3.2 Variation of Stiffness Reduction Factor with Opening Ratio of Infilled Panels

The computed results from the model of the infill frame for the various opening sizes and configurations considered in this work show that the stiffness reduction factor decreases with increase in opening ratio of the infill panel generally from a value of 1.0 for the complete rigid frame ($\beta = 0$) to a value of about 0.45 for the bare frame ($\beta = 1.0$). This decrease is very significant again for a case of opening on the compressed diagonal area. A plot showing the stiffness (K) against the opening ratio (β) and the estimated stiffness reduction factor (λ) against opening ratio is shown in Figures 12 to 14 for the three different configuration considered in this research. Also reasonable relationship relating the basic variables, the opening ratio (β) and the stiffness reduction factor (λ) is obtained in Equations 14 to 16 for cases of opening on the compressed diagonal, above the compressed diagonal and below the compressed diagonal respectively. An average correlation coefficient (R^2) of 0.64 was obtained in the plots.

$$\lambda = 0.377\beta^{-0.17} \qquad (14)$$

$$\lambda = 0.452\beta^{-0.14} \qquad (15)$$

$$\lambda = 0.502\beta^{-0.12} \qquad (16)$$

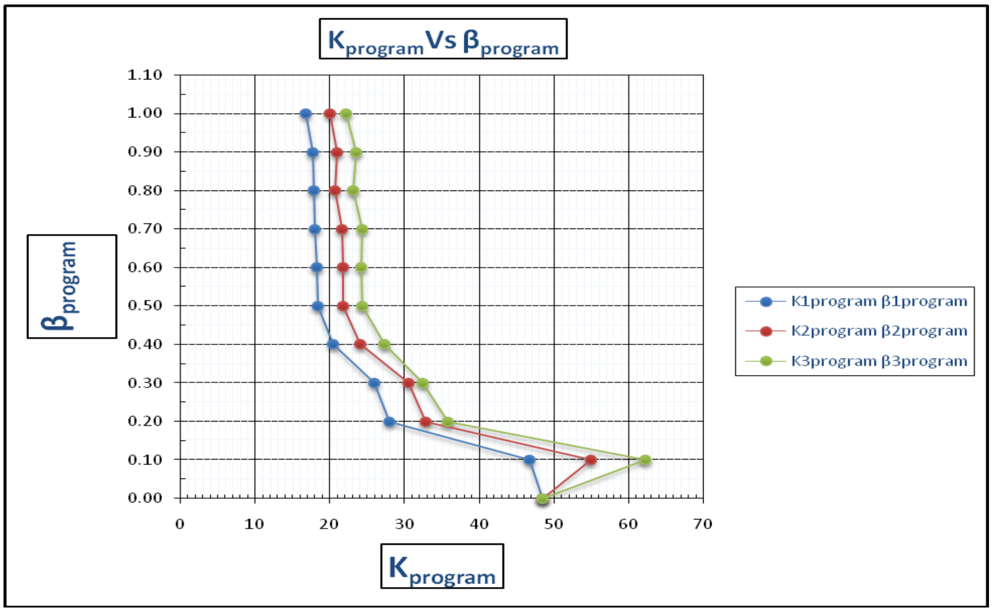

Figure 12: Variation of Stiffness against Opening Ratio for different Configurations

(Values from Developed program)

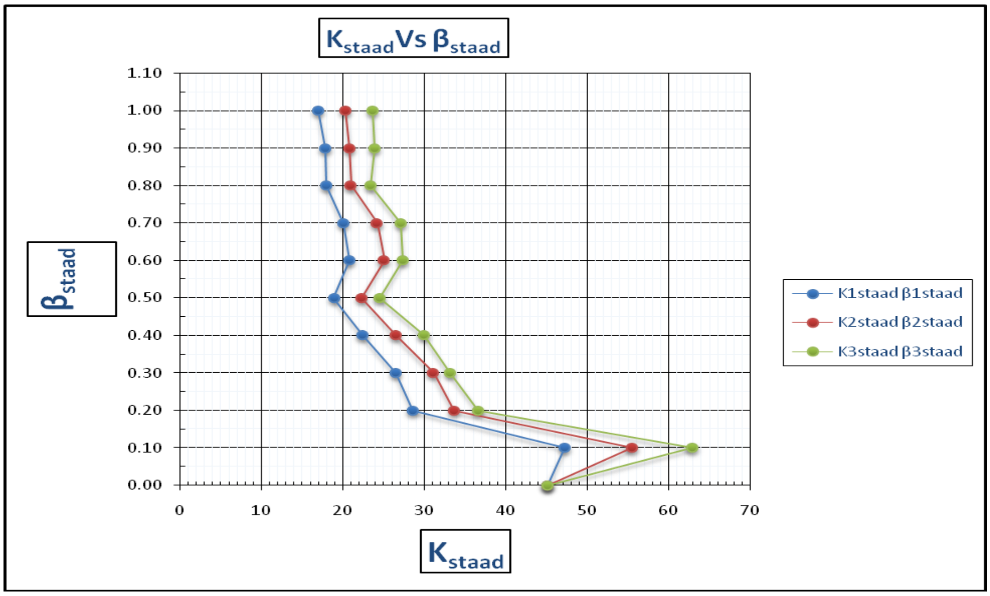

Figure 13: Variation of Stiffness against Opening Ratio for different Configurations

(Values from STAAD. Pro V8i program)

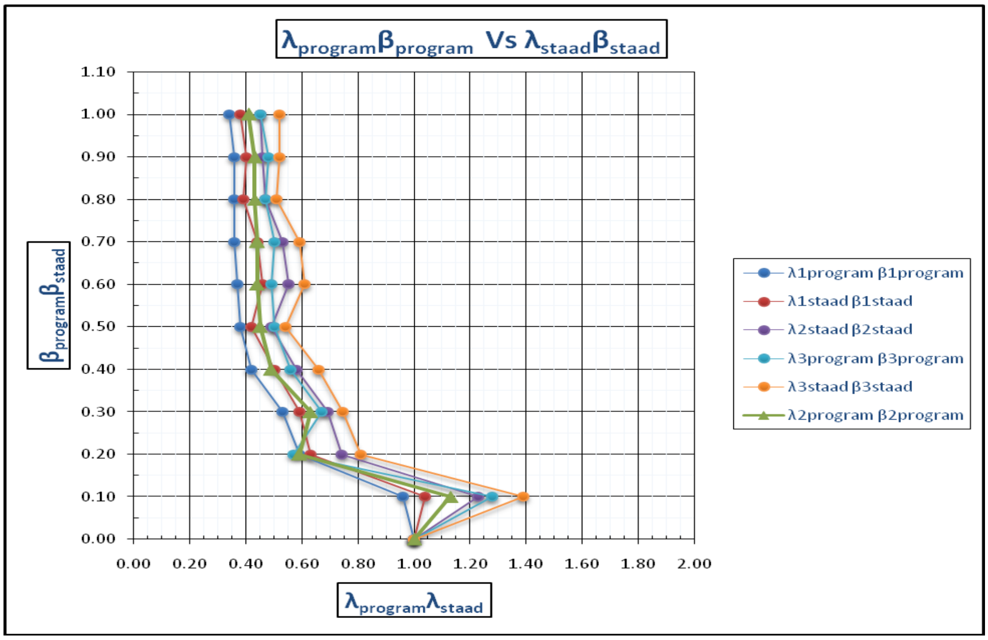

Figure 14: Variation of Stiffness Reduction Factors against Opening Ratio for different Configurations *(Values from Developed and STAAD. Pro V8i program)*

3.3 Validation of the Developed Program

The results of the developed FE program is compared with the results obtained from STAAD Pro V8i software, which confirm that the average error between the two models is about 4.45 %, while the highest and least deviations of 12.08% and 1.87% occurred on structural model with ACD80 - opening above the compressed diagonal (80% opening ratio) and BCD80 - opening below compressed diagonal (80% opening ratio). There is a close agreement of the results of the developed FE program and the commercial software indicating the adequacy of the developed FE program to reproduce the response of infill frames with different configurations of sizes of openings. A plot clearly showing this comparison is seen in also in Figures 10 to 14, which display a summary of result output on all structural models.

4. CONCLUSION

From the results obtained we arrive at the following specific conclusions:

i. The lateral deflection of the infilled frame decreases with reduction in opening ration to about 50% suggesting a significance of infilled frame to the sway stability of portal frames.

ii. This deflection is also more rapid in the case of opening on the compressed diagonal by about 20% against other two cases.

iii. The lateral stiffness with respect to size and position of openings is closely related to the corresponding deflection, suggesting an increase in stiffness against decrease in deflection.

iv. It is further established that the estimated stiffness reduction factors proposed for diagonal strut modeling (macro-modeling) of infilled frames to account for varying configurations and sizes of opening vary from a value of 1.0 for the complete rigid frame ($\beta = 0$) to a value of about 0.45 for the bare frame ($\beta = 1.0$).

v. The variation in stiffness and the stiffness reduction factors is somewhat insignificant beyond an opening ratio of 0.5 irrespective of all cases.

vi. Finally reasonable relationships relating the stiffness reduction factor (λ) and the solidity ratio (β) were obtained in exponential form.

vii. The results from the developed program were found to compare favorably with those from the program with an average difference of about 4.45%.

4.1 Recommendations

I. An extension of this work can be carried out using varying loads to a failure state.

II. The developed FE model can be improved to investigate stress distribution on the composite structure and hence determine areas of critical stresses and also plane of weaknesses along the infill and frame interface.

III. The present study was limited to brick infill material. It would be of great practical benefit if this can extended to other forms of infill materials such as block work, cement stabilized lateritic blocks e.t.c.

IV. It is also recommended that the stiffness factors developed in this work be implemented on the modeling of multi-storey infilled frames.

V. Improved stiffness reduction formulae for infilled frames with openings subjected to dynamic load regime is required.

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