NONLINEAR STATIC ANALYSIS FOR SHEAR OF SHORT COLUMNS IN BUILDINGS STRENGTHENED BY CONCRETE JACKETING

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Abstract

Brittle failures of weak shear-critical reinforced concrete (RC) columns in a building may occur during an earthquake, leading to its collapse. The research focused on seismic strengthening of such short columns using concrete jacketing technique.

The study reported in this paper proposes, validates and demonstrates a methodology to conduct nonlinear static analysis of a building with short jacketed columns. This type of analysis requires the shear force versus shear deformation data as input, popularly known as shear hinge property, in addition to the flexural hinge property for the columns. In this paper, a generalized truss analogy is proposed to predict the post-cracking nonlinear shear force versus shear deformation behavior of a short column (without and with jacket) under combined lateral and axial loads. It combines the concepts of truss analogy with softening of the concrete struts under biaxial tension-compression, generated due to shear. First, the formulation satisfying the equilibrium of forces, compatibility of strains and constitutive relations of materials is briefly explained. Next, the proposed method of analysis is validated based on the behavior of jacketed column specimens, tested as part of this research. The predicted behavior of a specimen was found to corroborate well with the test result, proving the applicability of the proposed method.

Finally, the results of nonlinear static analyses of a model building are included. A typical RC framed building with an open ground story (OGS) supported on short columns was selected. Computational models were simulated using a commercial software for two conditions of the OGS columns, without and with jackets. The shear hinge properties developed based on the proposed method were given as input. The results from the pushover analyses showed the improvement in performance of the columns after jacketing. This demonstrates the utilization of the proposed method in professional practice, for performance-based evaluation of buildings with short columns strengthened by concrete jacketing.

Keywords: building; column; concrete jacket; pushover; shear hinge

1. Introduction

Post-earthquake reconnaissance studies have reported severe damage to structures along with casualties. Failure of the columns in the open ground stories (OGS) led to pancake-type collapse of several reinforced concrete (RC) buildings during the earthquake in Bhuj, India, 2001 (Jain et al., 2001) [1]. These incidences have exposed the vulnerability of existing structures to seismic forces. Seismic retrofitting/strengthening of existing structures at global and local levels can reduce their vulnerability (Seismic Rehabilitation of Concrete Structures, 2007 [2], Handbook on Seismic Retrofit of Buildings, 2008 [3], Seismic Evaluation and Retrofit of Existing Buildings, 2017 [4]). To mention a few, addition of shear/infill/wing walls, reduction of mass/irregularity, inclusion of energy dissipation/base isolation measures etc., are some global strategies for RC buildings. Local strategies include jacketing the members such as beams, columns etc., using RC, steel, fiber reinforced polymer etc.

The present research examines strengthening of short columns in buildings, using RC jacketing technique. A common occurrence of short columns is in the OGS. The height of the story for car parking is typically low, which leads to reduced height-to-depth ratio of the columns about the major axis. Moreover, the depth-to-width aspect ratio of these columns can be large to flush them with the infill walls in the upper stories. Such 'wall-type' columns are more susceptible to brittle shear failure than flexural failure. The jacketing technique involves preparation of surface of an existing column, assembly of longitudinal and transverse steel reinforcing bars around it and casting a layer of concrete. The casting can be either by shotcreting or by placing flowable concrete, in the thin annular space between the existing column and formwork for the jacket.

An analysis for a retrofit scheme involves pre- and post-retrofitting analyses of the structure. In a performance based approach, modeling of the nonlinear behavior of a member of the structure needs attention. In the present research, an analytical procedure was developed and corroborated with experimental results, to model the shear behavior of short columns, both before and after retrofitting. The post-cracking nonlinear shear deformation was modeled using a generalized truss analogy, along with the softened truss model. The nonlinear curve can be suitably idealized to piece-wise linear curve for modeling the shear hinge property of a column in a nonlinear static analysis, under monotonically increasing lateral load (pushover analysis) for a building. The concept of generalized truss analogy, its validation using test results and its application in a pushover analysis of a model multi-storied building, before and after retrofitting the columns in the OGS, are discussed in this paper.

2. Research Background and Motivation

Previous studies conducted by other researchers on shear deformation, models to predict behavior of concrete jacketed columns and tests on jacketed columns are briefly discussed in this section. The motivation for present research is mentioned.

2.1 Models for Predicting Shear Deformation of RC Members

Expressions to compute pre-shear-cracking and post-shear-cracking stiffnesses were given based on a linear truss analogy by Park and Paulay (1975) [5]. Nonlinear shear deformations of RC membrane elements can be predicted based on the modified compression field theory (MCFT) (Vecchio and Collins, 1986 [6]), or the softened truss model (STM) (Hsu, 1988 [7]). The MCFT was applied to propose shear deformation models for the post-peak behavior of RC columns (Ranzo and Petrangeli, 1998 [8]; Petrangeli, 1999 [9]). The STM was further developed to the softened membrane model by incorporating the Poisson's effect in two-dimensional elements (Hsu and Zhu, 2002 [10]). An idealized tri-linear model to predict the deformation of columns based on a drift approach was suggested by Elwood and Moehle (2004) [11]. Setzler and Sezen (2008) [12] developed a model to predict the lateral load behavior of short columns with reduced amount of ties. Compatibility strut-and-tie model for predicting the behavior of shear critical members, considering the softening of diagonal concrete strut, was proposed by Karthik et al. (2016) [13]. The fiber-based modeling of RC members typically does not consider the nonlinearity in the shear behavior.

2.2 Models for Predicting Behavior of Jacketed Columns

A jacketed column has two parts in the section, the inner portion and the jacket, integrated at the interface. It is a composite section with heterogeneous concrete properties. A few models predicting the strength and behavior of jacketed columns are available, with or without considering the slip at the interface. Jacketed column sections were considered to be monolithic, on satisfying certain properties pertaining to concrete strength, amount of reinforcement, axial load etc. (Bousias et al., 2007) [14]. Monolithic behavior factors were proposed for stiffness and strength, for transforming the composite section to an equivalent monolithic section (Dritsos, 2007) [15]. Refined factors were derived by Lampropoulos and Dritsos (2010) [16] considering shrinkage of jacket concrete, as it reduces its compressive strength substantially. Correlating coefficients were further derived for displacements at yield and failure, considering different levels of axial loads and thickness of jacket (Lampropoulos et al. 2012) [17]. Good predictions of flexural behavior based on layered analysis were achieved by Kaliyaperumal and Sengupta (2008) [18]).

2.3 Experimental Investigations on Jacketed Columns

The repair and strengthening types of jacketing showed similar performances, when the additional concrete and ties were adequate in each method (Bett et al. 1988 [19]; Rodriguez and Park, 1994 [20]). Sudden drop in the shear capacity of jacketed columns beyond the peak was observed due to the incapability of the jacket mortar in transferring shear (Fukuyama et al., 2000) [21]. Deformation and energy dissipation capacity improved in a lap-spliced jacketed column, irrespective of the lap length (Bousias et al. 2007) [22]. Enhancements in strength and stiffness were observed even if the interface was not additionally treated (Vandoros and Dritsos, 2008) [23]. Flexural capacity and ductility of columns were found to increase after jacketing, as per the predictions (Kaliyaperumal and Sengupta, 2014 [24]).

2.4 Motivation for Present Research

In the literature reviewed, there was no specific study on predicting the shear behavior of jacketed columns. Most of the reported works on strengthening dealt with capacity-based design approach, wherein the brittle shear failure was avoided after jacketing. The available data on jacketed column is related to flexure-based behavior, which cannot be used for the development of shear hinge property for a wall-type column in a pushover analysis of a building. The present research thus aimed to study specifically the shear behavior of short jacketed columns. The results can be applied to study the effect of jacketing of the columns in the OGS.

3. Generalized Truss Analogy

A generalized truss analogy is proposed to predict the nonlinear shear force versus shear deformation behavior of a short column, subjected to lateral and axial loads. The method of analysis is extended to shear analysis of jacketed columns. The simultaneous equilibrium and compatibility conditions, and constitutive relations for concrete and steel bars are solved by an algorithm to obtain the shear behavior curve. This curve is used to develop the piece-wise linear shear hinge property of a column, as required in the pushover analysis for a building using a commercial software.

A short column in a building was considered, with ends subjected to relative lateral displacement only, as shown in Fig. 1(a). On application of increasing lateral load (V) and in the presence of service-level compressive axial load (P) due to gravity, and widely spaced ties, the diagonal shear cracks extend to form a diagonal strut. The column fails due to crushing of the strut, either before or after yielding of the ties. An ideal form of the strut with constant width is considered in the formulation of generalized truss analogy. The thickness of the strut is considered to be same as the width of the column in the two dimensional deformation. The column is idealized as an isolated truss panel, as shown in Fig. 1(b). The truss panel comprises of the concrete strut inclined at an angle θ with the vertical, as well as longitudinal and transverse reinforcement members, with lumped properties. The forces are marked, with the corresponding stresses and strains mentioned in parenthesis.

An algorithm to trace the shear force versus shear deformation of the column beyond shear cracking is presented in Murugan and Sengupta (2018 a) [25]. The computational loop involves the following forces, stresses and strains in the equilibrium and compatibility equations, and the constitutive relationships:

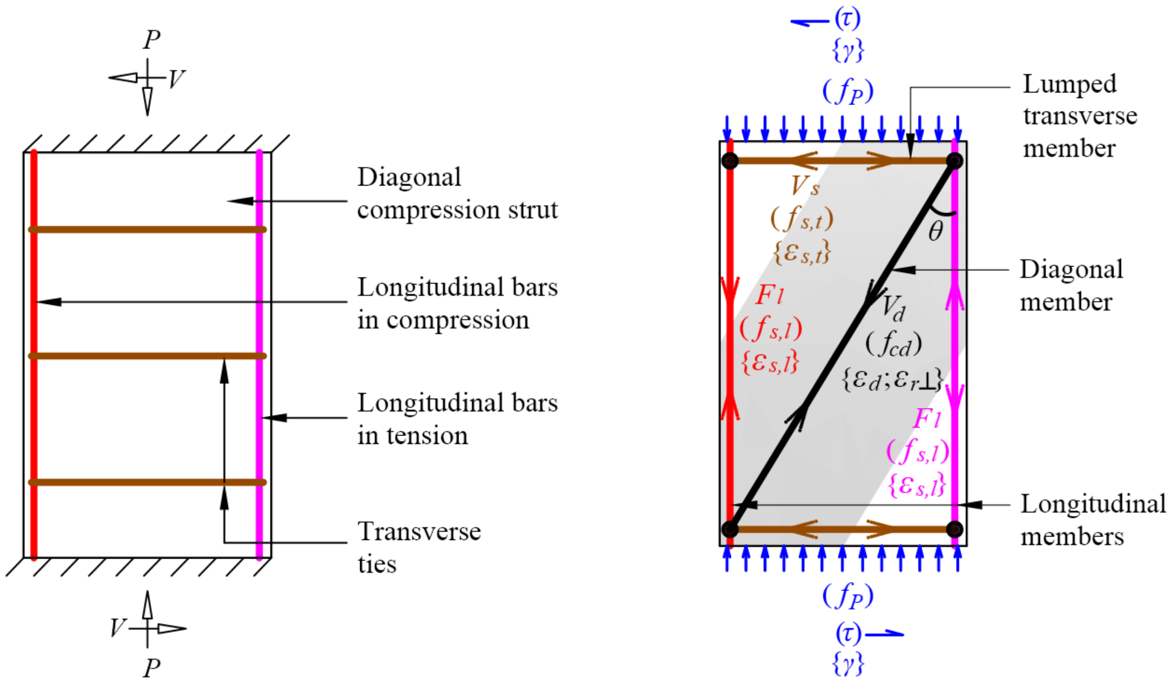
(a) Forces: compressive force along the strut V_d, tensile forces in the transverse ties V_s, tensile forces in the longitudinal bars due to the lateral load F_l.

(b) Stresses: stress in the strut due to the lateral load f_{cd}, stress in the strut due to axial compression f_P, stress in longitudinal bars $f_{s,l}$, stress in transverse ties $f_{s,t}$.

(c) Strains: principal diagonal compressive strain in the concrete of the web region of the section due to shear ε_d, orthogonal average tensile strain in concrete ε_r, average strain in transverse ties $\varepsilon_{s,t}$, average strain in longitudinal bars $\varepsilon_{s,l}$, overall shear strain of the panel γ.

The constitutive relationship proposed by Hsu (1993) [26] considering gradual softening of the concrete strut due to orthogonal tensile strain, was adopted. An elastic-perfectly plastic stress versus strain model was considered to be adequate for the steel bars. The algorithm was terminated when the total stress along the strut reached the concrete crushing strength, considering the effect of softening.

To apply this analogy for a jacketed section, the composite properties were considered through a sandwich model. The properties of the inner and jacket concrete were considered individually. This model assumed a no slip condition at the interface between the inner and jacket portions.



(a) Longitudinal section of a column (b) Truss model with forces, stresses and strains

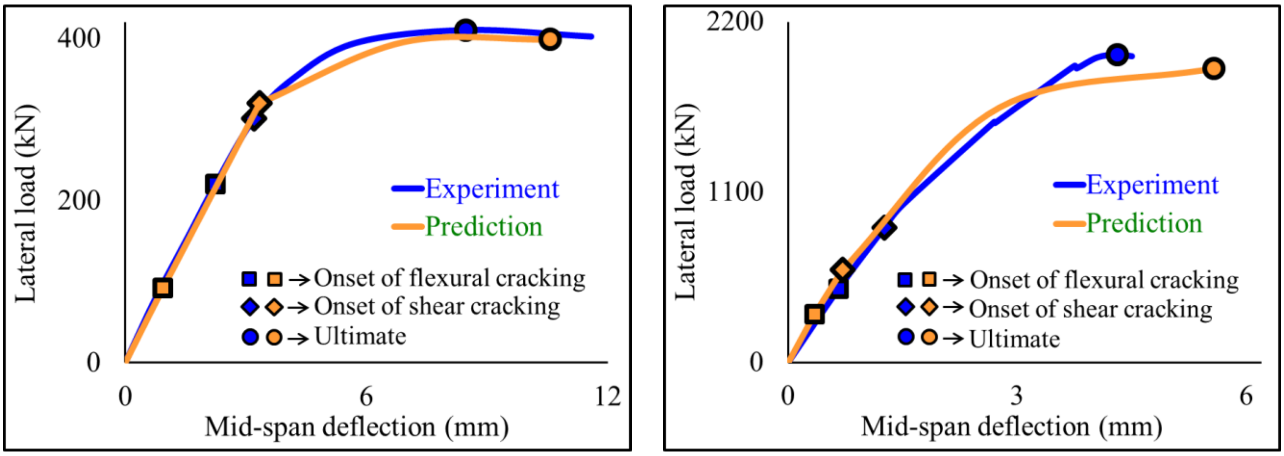
Fig. 1 – Idealization of a column for the truss analogy

4. Validation of Generalized Truss Analogy

The proposed analogy was validated by comparing the predicted results with those from the conducted tests (Fig. 2). Specimens without jackets and specimens with three types of interfaces between the inner concrete and jackets were studied (Murugan and Sengupta (2018 b) [27]. In this paper, two representative specimens are chosen for demonstration, one without jacket and the other with jacket. A specimen without jacket had dimensions of 230 mm (width) × 400 mm (depth) × 2000 mm (length). The dimensions and minimum amount of ties are based on typical data of short columns in a building designed for gravity loads only. The inner portion of a specimen with jacket had similar dimensions and reinforcement. The thickness of the jacket was 80 mm, and was made of additional longitudinal and transverse reinforcement, along with flowable microconcrete. A specimen was first pre-compressed and then was subjected to increasing lateral load at mid-span till failure. The details of the specimen preparation, testing procedure, failure modes and test results are provided in Murugan (2018) [30].

In a prediction of the lateral load versus mid-span deflection behavior, at each load step, the flexural component of deformation was added to the shear deformation to get the total deflection. The analysis for flexural or shear deformation till cracking was based on the linear elastic theory. Beyond flexural cracking, the flexural deformation was calculated based on nonlinear moment versus curvature analysis of the specimen section. Beyond shear cracking, the shear deformation was calculated based on the proposed method. The results are presented as lateral load versus deflection plots in Fig. 3(a) and Fig. 3(b). A reasonable corroboration of the predicted and test curves was obtained for both the types of specimens. This validates the application of the proposed analogy and computational algorithm for estimating the behavior of short columns under monotonically increasing lateral loads. Next, the application in pushover analysis of a model multi-storied building is demonstrated.

Fig. 2 – Test set-up showing a specimen under simultaneous lateral load and axial compression



(a) Specimen without jacket

(b) Specimen with jacket

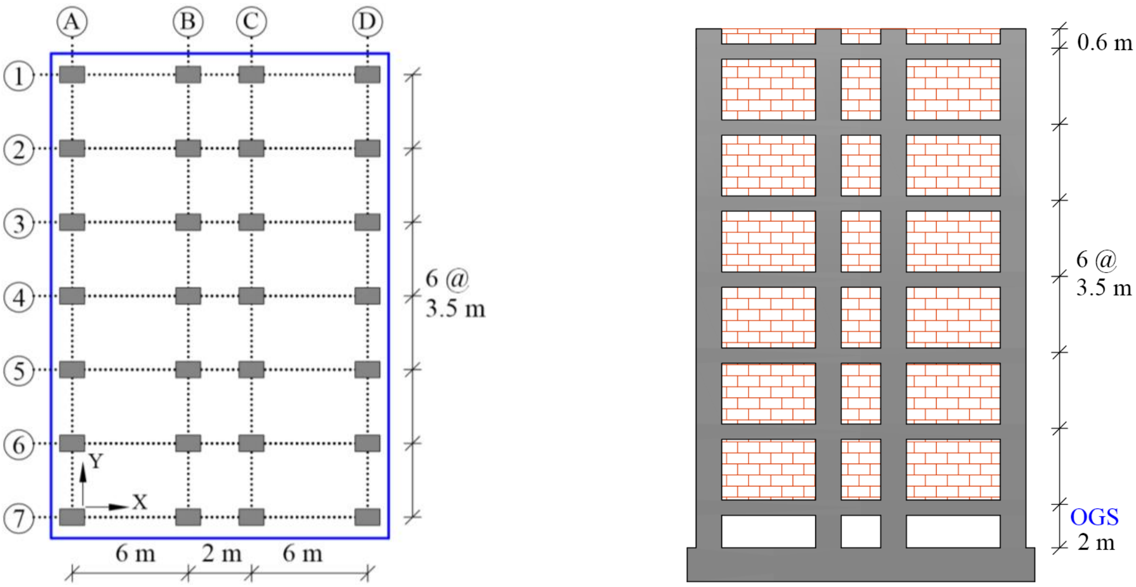
Fig. 3 – Comparison of predicted and test results

5. Application of Generalized Truss Analogy

A numerical study was conducted to predict the behavior of an idealized multistoried framed building with short columns in the OGS under lateral loads, as an application of the generalized truss analogy in pushover analysis. The nonlinear shear hinge properties of a column without and with jacket, were developed based on the proposed method. To show the effectiveness of strengthening of the columns in the OGS with concrete jackets, only this retrofit strategy was considered. The schematic plan and front elevation of the selected building are shown in Fig. 4(a) and Fig. 4(b), respectively. Two computational models were developed:

(a) Model BM with columns in the OGS without jackets.

(b) Model BJ with jacketed columns in the OGS.



(a) Plan at foundation level

(b) Front elevation

Fig. 4 – Plan and elevation of the selected building

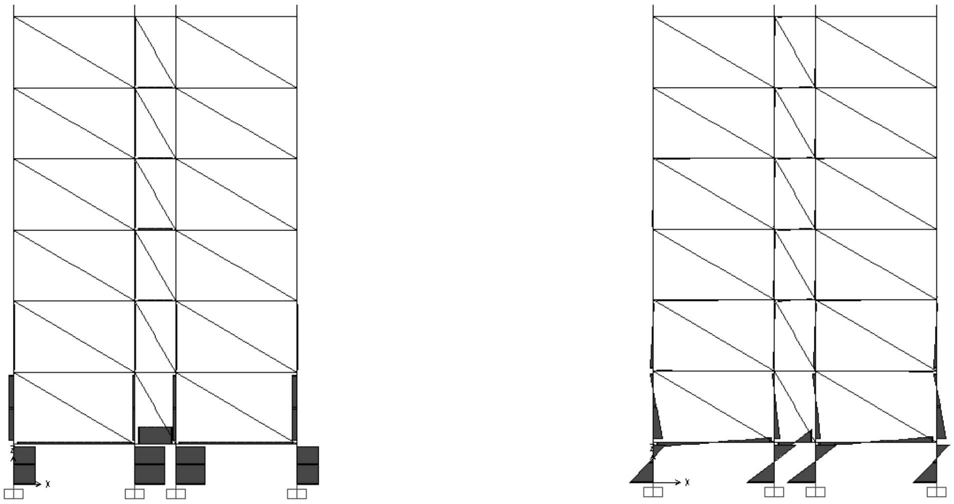
5.1 Analysis of Model BM

First, Model BM was analyzed for gravity loads, with the data shown in Table 1. The member sizes and reinforcement were selected based on gravity load design criteria. The columns in a certain story were divided into four groups based on the tributary areas for gravity loads: corner columns, edge columns along X, edge columns along Y and interior columns. The reinforcement for all the columns in a group was same based on satisfying the moment demand in presence of axial load. Minimum amount of ties was provided in a column. Similarly, the beams in all the floors were grouped as interior or exterior beams, and designed based on the moment and shear demands. The beams and columns were modeled as frame elements. Considering raft foundation, the bottom of each OGS column was modeled as fixed.

Next, for the lateral load analysis, a rigid diaphragm was considered at each floor level to account for the in-plane stiffness of slabs. A brick masonry infill wall was considered to be present on all the beams, to demonstrate increased stiffness in the upper stories of an OGS building. An infill wall was modeled as an equivalent diagonal compression strut. The lateral loads were computed based on the equivalent static method of analysis of IS 1893: 2016 [28]. Results from the lateral load analysis showed high shear demand with reversed curvature bending in the OGS columns (Fig. 5(a) and Fig. 5(b)).

Table 1 – Building data

Size of members	Slabs	125 mm thick
	Beams	200 mm × 300 mm
	Columns	230 mm × 350 mm
	Infill walls	230 mm thick
Materials	Characteristic compressive strength of concrete	20 N/mm^2
	Characteristic yield strength of steel	415 N/mm^2
	Characteristic compressive strength of brick masonry	7.5 N/mm^2
Gravity loads in addition to self-weight	Superimposed dead load	Floor finish - 1 kN/m^2
		Roof finish - 2 kN/m^2
	Live load	Floors - 2 kN/m^2
		Roof - 1 kN/m^2
Parameters for lateral loads	Zone factor (*Z*)	0.36 for Zone V
	Importance factor (*I*)	1.0 for Residential
	Response reduction factor (*R*)	3.0 for OMRF
	Type of soil	Type II (Medium)



(a) Shear force diagram (b) Bending moment diagram

Fig. 5 – Typical distribution of member forces from lateral load analysis

A pushover analysis for lateral loads was done incorporating material nonlinearity through assigning point plastic hinges to the members. Flexural and shear hinges were assigned to the columns and beams, and axial hinges were assigned to the infill struts (Fig. 6). For a beam, flexural and shear hinges were assigned at both the ends of the member. For a column, one shear hinge was assigned at the mid-height for easy identification of shear deformation. For an infill strut, an axial hinge was assigned at the middle. A tri-linear flexural hinge property for a member was developed based on the moment versus curvature analysis for the section of the member group. A bi-linear shear hinge property of a column group was developed based on the proposed method of analysis. The points of origin, shear cracking and ultimate were connected. Due to the presence of weak concrete, cracking was followed by crushing, without yielding of ties. For a column, a hinge property was developed individually for either axis of bending, major and minor, for the respective pushover analysis.

After assigning the hinges, the model was first subjected to load-controlled gravity push till the service level gravity loads. Next, the model was subjected to pushes along the X- and Y- directions separately, which are referred to as Push-X and Push-Y, respectively. The sectional details of OGS column, developed hinge properties and results are compared along with those from the analysis of Model BJ, as presented next.

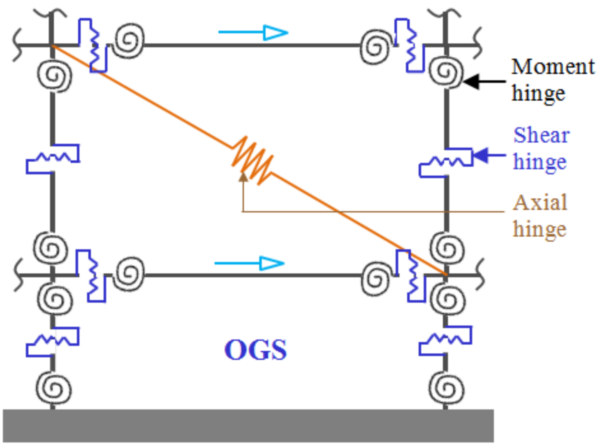


Fig. 6 – Schematic representation of assigning of hinges

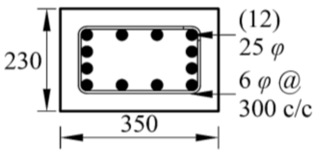
5.2 Analysis of Model BJ

A jacketed column in the OGS was designed by trials based on the recommendations of IS 15988 : 2013 [29]. Fig. 7(a) and Fig. 7(b) show the sectional details of an OGS column without and with jacket, respectively. A minimum thickness of 100 mm for the jacket, with adequate concrete cover for the bars, was chosen. Intermediate longitudinal bars for lateral support of the ties in jacket are not shown. The shear force (V) versus deformation (γ) hinge properties of these columns were then developed based on the generalized truss analogy algorithm. The salient points of the properties are shown in Table 2. Comparison of the developed hinge property curves (V2 hinge) for corner columns in OGS (typical), without and with jacket is shown in Fig. 7(c). The substantial increase in shear strength is due to the close spacing of the additional ties, as per the requirement for the vertical irregularity. The revised hinge properties were assigned to the respective column elements and the pushover analyses were run.

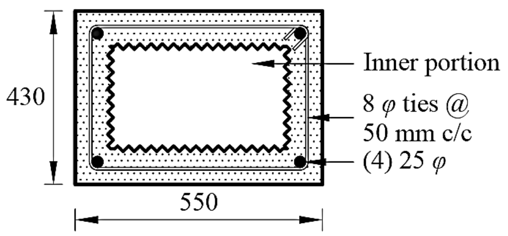
Table 2 – Shear hinge properties for OGS columns

Hinge	Group	Axial force (kN)	Model BM				Model BJ			
			Cracking		Ultimate		Cracking		Ultimate	
			V	**γ**	**V**	**γ**	**V**	**γ**	**V**	**γ**
V2 - major axis bending	Corner	993.7	92.0	0.0002	159.0	0.0035	621.9	0.0002	1152.5	0.0027
	Edge X	1177.4	81.9	0.0001	165.3	0.0039	664.6	0.0003	1226.8	0.0028
	Edge Y	1113.6	85.6	0.0001	163.1	0.0037	650.1	0.0003	1201.5	0.0028
	Interior	1349.5	71.0	0.0001	170.8	0.0043	702.3	0.0003	1292.9	0.0030
V3 - minor axis bending	Corner	993.7	92.0	0.0002	118.9	0.0033	621.9	0.0002	919.8	0.0028
	Edge X	1177.4	81.9	0.0001	122.6	0.0036	664.6	0.0003	978.1	0.0029
	Edge Y	1113.6	85.6	0.0001	121.3	0.0035	650.1	0.0003	958.2	0.0028
	Interior	1349.5	71.0	0.0001	125.8	0.0038	702.3	0.0003	1030.0	0.0030

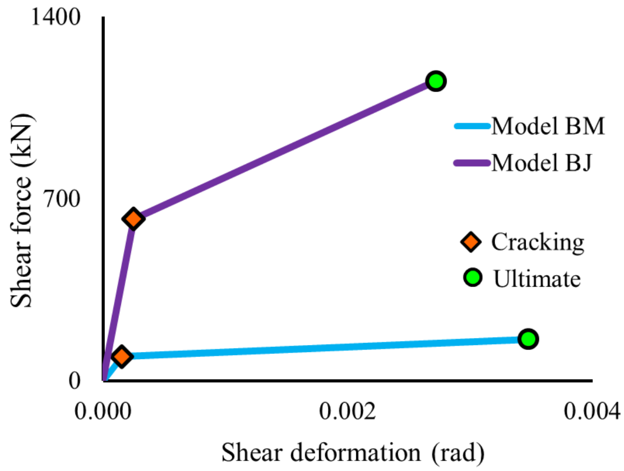
Note: $V \rightarrow$ Shear force (kN); $\gamma \rightarrow$ Shear deformation (rad)



(a) Cross-section without jacket



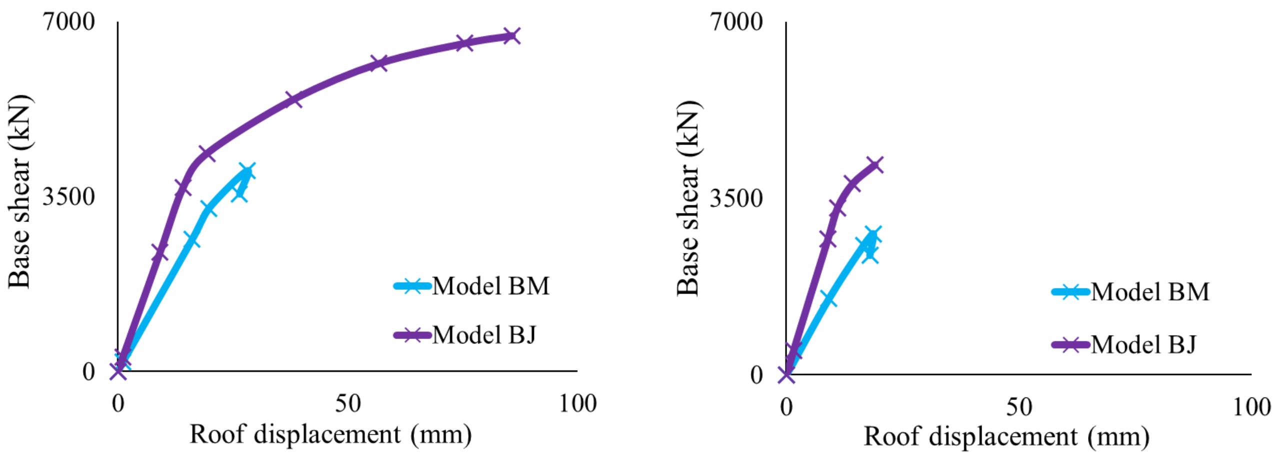
(b) Cross-section with jacket



(c) Comparison of shear hinges for corner columns (Axial force level: 993.7 kN)

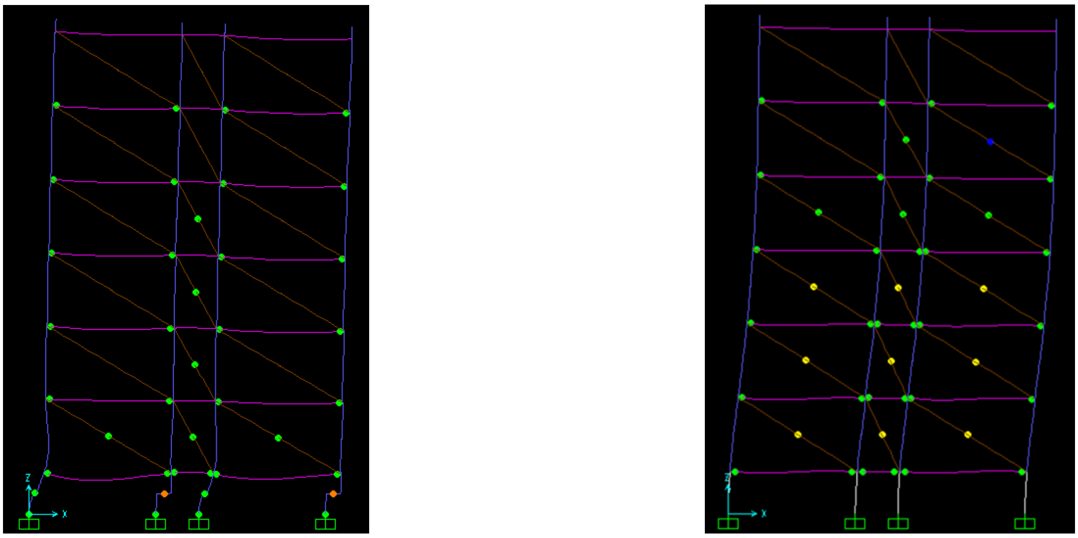
Fig. 7 – Cross-section and typical shear hinge properties of OGS columns

The pushover curves for the two building models pertaining to the final step of pushover analysis are compared in Fig. 8(a) and Fig. 8(b). Improvements in lateral load capacity and roof displacement are observed after jacketing, for Push-X. However for Push-Y, failure in minor axis bending leads to limited enhancement in lateral load capacity. The hinge formation patterns at this step are shown in Fig. 9(a) and Fig. 9(b), for the two models. OGS columns did not develop any hinge in Model BJ. At the peak load, a few beams in the first floor failed in shear, or the infill walls failed. Introducing shear walls appropriately will result in better performance.



(a) Push-X Push-Y

Fig. 8 – Comparison of pushover curves



(a) Model BM (Lateral load level: 3552.4 kN) (b) Model BJ (Lateral load level: 6711.0 kN)

Fig. 9 – Hinge patterns at the final steps of pushover analysis (Push-X)

6. Summary and Conclusions

A methodology to conduct nonlinear static analysis of a reinforced concrete building with short wall-type columns is discussed in this paper. The summary and conclusions from the present research are as follows.

(a) A generalized truss analogy is proposed to predict the post-cracking shear force versus shear deformation behavior of a short column, without and with jacket. This analogy idealizes a column as a truss panel based on the observed behavior under shear failure. It satisfies equilibrium of forces and compatibility of strains in concrete struts and steel ties, and constitutive relations of the materials at each step of lateral load. The softening of the concrete strut due to orthogonal tensile strain in the web region of the column section is considered. To apply the analogy for a jacketed section, the composite properties were considered through a sandwich model.

(b) The proposed method was validated with tests conducted as part of this research. The predicted results corroborated well with the test results of the lateral load versus deflection behavior specimens, with and without jacket. This proved the applicability of the suggested method to determine the shear deformation of short columns.

(c) The application of this method in professional practice was demonstrated by using it to develop shear hinge properties of OGS columns, without and with jacket, in a selected building model. The model was subjected to nonlinear static pushover analysis using a commercial software. The presented results of the numerical analysis showed the improvement of the performance of columns after jacketing. The building analysis can be further extended for value engineering of alternative retrofitting schemes with combinations of local and global strategies.

Certain guidelines for concrete jacketing of columns in buildings were compiled based on the present research (Murugan, 2018) [30]. The guidelines provide the detailing of reinforcement and method of execution of concrete jacketing of columns.

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