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Performance Evaluation of RC Beam-Column Connections Using Strut and Tie Method

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ABSTRACT

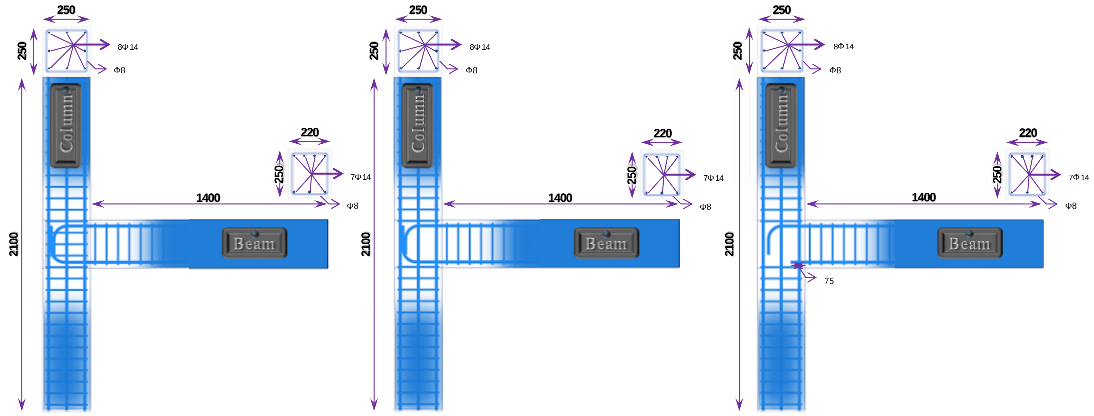
This paper presents an application of nonlinear strut-and-tie model (NSTM) for analysis of reinforced concrete (RC) external beam-column joints under lateral loading. The conventional STM is a calculation based on the force method exhibiting the internal forces in each component, it is unable to capture an inelastic response when RC beam-column joints undergo large displacement. Test results of three external beam-column sub assemblage frames with seismic and non-seismic detail in the joint region, were used to verify the applicability of the NSTM, respectively. In the joint region, nonlinear links of concrete and steel bar were applied to simulate a load-displacement response. The results, such as maximum loading capacity, lateral load-story drift relation and failure mode, obtained from both NSTM models and laboratory experiments were compared. It was found that the results from the analyses using the NSTM agreed well with the experimental results. Furthermore, the demand-to-capacity ratios of the nonlinear links, which represents the distribution of the internal force in the NSTMs' joint region, exhibit the failure location and the failure mode that compatible with the experimental result. Hence, the proposed model is capable of predicting the strength of external beam-column joint of RC frames under lateral loading.

Keywords:

RC beam-column joint, Seismic retrofitting, Prestressed joint enlargement, Strut and tie model, Non-seismic detailing.

1. Introduction

A strut-and-tie model (STM) is a discrete representation of the stress field developed within a concrete structure when subjected to external actions. Representation of structures with STMs allow analysis and design of reinforced concrete structural types to be performed in a rational manner. Within a STM, uniaxial stressed struts and ties having finite dimensions are used to represent the actual compressive and tensile stress fields respectively. The pin connections joining the struts and ties together correspond to the biaxial or triaxially stressed nodal zones. The strut-and-tie modelling technique has traditionally been employed in design practice to predict strength and to examine equilibrium of the applied loads, reactions, and internal forces for disturbed (D-) regions of structures with irregular geometry where the internal flow of force is not well known. Typically, such an investigation enables determination of suitable reinforcement detailing for the Dregions. Previous investigations by To et al. (2001, 2002a & 2002b) [1, 2] have demonstrated that a well-formulated STM is capable of capturing the monotonic response of reinforced concrete structures beyond the elastic range. In addition, the internal force demands developed in structural components can be effectively assessed using this modelling technique. The study reported in this paper is the extension of the application of strut-and-tie modelling technique to capture the nonlinear cyclic force displacement response of reinforced concrete structures. Practicing engineers and researchers need computational tools that accurately compute the nonlinear response of beam-column joints and, in particular. Such assessment can be done either with simplified and empirical models or with refined finite element (FE) models. An engineering tool of intermediate complexity, in comparison with FE models, is presented in this paper. This tool requires less computational effort and time than FE methods, using nonlinear truss elements with the added advantage that by using truss elements, the user gets a feeling for the internal force. This tool is able to satisfactorily compute the post cracking nonlinear response of RC beam-column joints in terms of global force displacement and the displacement at which concrete softening initiates or concrete crushes. In the current study, a strut and tie model is conceptually presented, implemented and validated by experimental results, to evaluate the joint shear strength and seismic performance beam-column joint. A strut and tie model was used to evaluate the joint shear strength. The model was verified and calibrated with experimental results of three beam-column joint with various reinforcement details. The Finite element computer program ABAQUS was employed for performing the analyses, with adequate stress-strain models for concrete and steel reinforcing bars were adopted. It is important to note that the objective of this investigation was not to obtain a replacement of the stress transfer mechanism that develops within a structure when subjected lateral loading. Instead, the nonlinear STMs described in this paper represent only a simple diagnostic tool for the seismic resistant analysis and design of complicated structural types. The STM models for reinforced concrete beam-column joints were considered to have three seismic and non-seismic details in the previous construction. The first case was considered to have seismic details, having sufficient hoops in the joint panel (C1). Non-seismic detail specimens (which cover most of the existing joints) include the lack of column hoops in the joint area (C2), and in the latter case, in addition to the previous weakness, no positive beam reinforcement was found in the joint area (C3) (Figure 1).



Specimen C1 Specimen C2 Specimen C3

Figure 1: Dimensions and reinforcement details of specimens C1, C2, and C3 (dimensions in millimeters).

2. Strut and Tie Modelling

Strut and Tie Modelling (STM) is a simple method which effectively expresses complex stress patterns as triangulated models. STM is based on truss analogy and can be applied to many elements of concrete structures. It is usually adopted to design non-standard elements or parts of elements of concrete structures such as pile caps, corbels, deep beams (where depth > span/3), beams with holes, connections, etc. where normal beam theory does not necessarily apply. STM is a powerful engineering tool where the engineer stays in control. With a reasonable amount of experience, it can help design engineers provide simple engineering solutions to complex structural problems. Possibly due to the lack of previous applicable design standards, STM was not popular in the use was generally limited. However, ACI and Euro code now includes STM, allowing and perhaps encouraging its more widespread use. STM is a lower bound plastic theory which means it is safe providing that:

1) Equilibrium is satisfied, 2) The structure has adequate ductility for the assumed struts and ties to develop, 3)Struts and ties are proportioned to resist their design forces.

The design process for strut-and-tie models can be summarized into four main stages:

1) Define and isolate B- and D- regions (i.e. beam or Bernoulli and disturbed or discontinuity regions), 2) Develop a STM - a truss system to represent the stress flow through the D-region and calculate the member forces in the truss, 3) Design the members of the STM - dimension and design the truss members to resist the design forces, 4) Iterate to optimize the STM as necessary to minimize strain energy.

The strut-and-tie model representing the stress fields within an external beam-column joint was developed based on the results of force flow in the finite element analysis. Truss idealization of an exterior beam-column joint is shown Figure 2.

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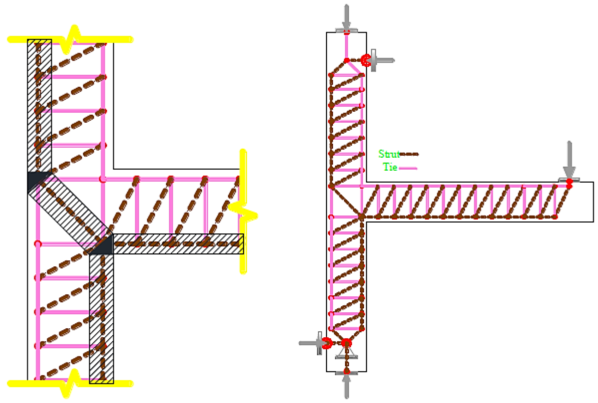

(a) Main strut in the joint region (b) STM of control specimens

Figure2: Truss idealization of an exterior RC beam-column joint.

3. Nonlinear Truss Modelling Approach

Nonlinear Strut and Tie Modellingapproach proposes the development of a classic STM model and its further revision through a non-linear model. The analysis performed in this study consider both material behaviors, the linear elastic and the non-linear. The constitutive model of plastic damage available in Abaqus software, called CDP (Concrete Damaged Plasticity) has been adopted in the present study, for the nonlinear analysis of the elements in concrete reinforced by FEM. In the CDP model, the stiffness deterioration is modeled by defining the relationship between stress and effective stress. Using numerical damage and effective stress based on Equation (1), a relationship is created between damage and plasticity which presents the stress-strain model in CDP (Genikomsou & Polak, 2015) [3].

$$f = (1-d)E_0^{el}\left(\varepsilon - \varepsilon^{pl}\right) = (1-d)f' \quad (1)$$

where: f is stress, d is a numerical variable of hardness damage) that has a value from zero to one (E_0^{el} is the initial elastic modulus, ε is the total strain, ε^{pl} is the plastic strain ($\varepsilon = \varepsilon^{el} + \varepsilon^{pl}$() and $f'$are the effective stresses (maximum compressive or tensile strength of concrete). The parameters required in the model of Concrete Damaged Plasticity are specified in Table 1.

Table 1. Parameters for concrete damage plasticity model.

Dilation Angle	Eccentricity	f_{b_0}/f_{c_0}	k_c	Viscosity Parameter
25	0.1	1.16	0.667	0.001

3.1. Compressive and Tensile behavior of Concrete

Thorenfeldt (1987) [4] equations (Equations (2) to (4)) have been used to model concrete behavior. The mechanical properties of the concrete used in the specimens are presented in Table 3.

$$\frac{f}{f_c'} = \frac{\varepsilon_c}{\varepsilon_0} \times \frac{n}{\left[n - 1 + \left(\frac{\varepsilon_c}{\varepsilon_0}\right)^{nk}\right]} \quad (2)$$

$$n = k = 1 \qquad {}^{\varepsilon}/_{\varepsilon_0} < 1 \quad (3)$$

$$n = 0.8 + \frac{f_c'}{17} \;, k = 0.67 + \frac{f_c'}{62} \qquad {}^{\varepsilon}/_{\varepsilon_0} > 1 \quad (4)$$

Where f_c' is the maximum compressive strength of concrete and placed on the metric system, ε_c is the total compressive strain, ε_0 is the strain as the maximum compressive stress of concrete ($\varepsilon_0 = 0.00078[f_c'(Mpa)]^{\frac{1}{4}}$). The non-elastic compressive strain $\left[\varepsilon_c^{in}\right]$ is used to determine the compressive behavior of concrete in the ABAQUS program, obtained from Equations (5) and (6).

$$\mathrm{\varepsilon_c^{in} = \varepsilon_c - \varepsilon_{0c}^{el}} \quad (5)$$

$$\mathrm{\varepsilon_{0c}^{el} = \frac{f_c}{E_0^{el}}} \quad (6)$$

Where, the ε_{0c}^{el} is the elastic compressive strain of the not affected concrete. The ABAQUS program defines the tensile behavior of concrete after its tensile failure. And we assume that the tensile stress of the concrete changes to a strain equal to ten times the strain such as tensile failure ($10\ \varepsilon_t'$)). According to

Figure 3, the stress-strain curves can be observed for compressive and tensile behavior of concrete.

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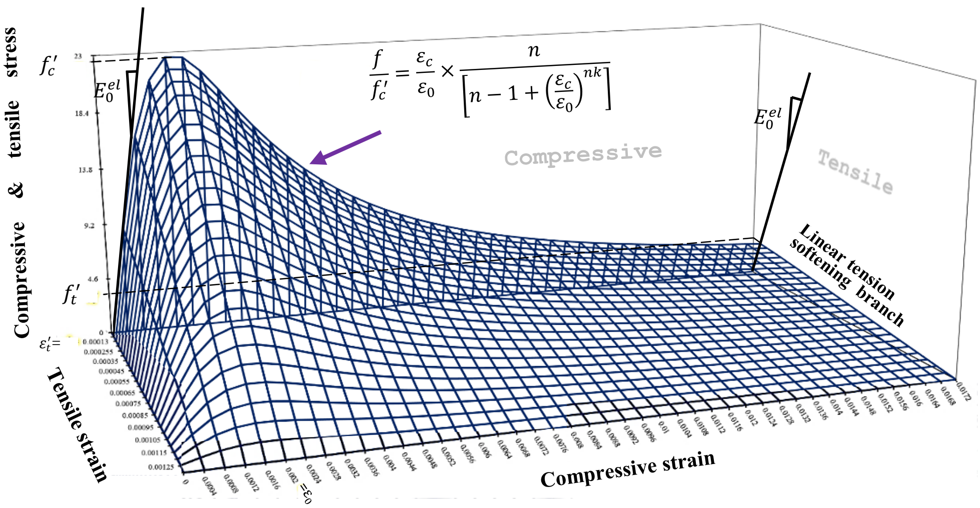

Figure 3: Stress-strain curves of concrete in tension and compression.

4. Details of Nonlinear Strut and Tie Modeling

The strut-and-tie model is formulated using three different element types. Type 1 elements are composed of a concrete strut and a rebar tie to represent the material behavior of diagonal mass concrete and replicate the transverse reinforcement in structural B-regions Type 2 elements that characterize flexural response of structural B-regions are composed of a concrete strut, a concrete tie, and a rebar strut-tie arranged in tandem to replicate, respectively, the concrete compression-carrying behavior, the concrete tension-carrying capability that is associated with the "tension stiffening effect," and the axial compression-tension carrying capability in reinforcement. The mass concrete located and Reinforcement located in structural D-regions is represented by type 3 elements, which consist of a concrete strut and a rebar tie arranged in tandem to replicate the compression-carrying behavior and tension-carrying capacity of concrete and reinforcement, respectively. Information regarding the computation of other element properties is summarized in Table 2. The specifications of the Strut and tie model developed in ABAQUS software are shown in Figure 4.

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Table 1. Summary of Element Properties for Strut-and-Tie Models

Element type	Model element	Area	Effective strength (MPa)	Elastic stiffness (MPa)	Stress-strain characteristic
1	Diagonal concrete strut	Acs is evaluated by multiplying the strut width, measured as the average distance between adjacent concrete struts, by the effective strut depth, measured as total width of the structural component.	23.0 (According to laboratory test)	22540 (According to laboratory test)	Based on the Thornenfeldt equations (Thorenfeldt, 1987)
	Transverse rebar tie	Av=Vn / fvy	350 (According to laboratory test)	200000 (According to laboratory test)	Based on bilinear behavior and type of isotropic hardening
2	concrete strut-tie	*Ac* is evaluated as the area between the neutral axis position and the extreme compression edge of the section measured at the first yield limit state.	23.0 (According to laboratory test)	22540 (According to laboratory test)	Based on the Thornenfeldt equations (Thorenfeldt, 1987)
	Rebar strut-tie	The size of the reinforcement in the area	460 (According to laboratory test)	200000 (According to laboratory test)	Based on bilinear behavior and type of isotropic hardening
3	Concrete struts in D-region	Acs is evaluated by multiplying the strut width, measured as the average distance between adjacent concrete struts, by the effective strut depth, measured as total width of the structural component.	23.0 (According to laboratory test)	22540 (According to laboratory test)	Based on the Thornenfeldt equations (Thorenfeldt, 1987)
	Rebar tie in D-region	Av=Vn / fvy	350 (According to laboratory test)	200000 (According to laboratory test)	Based on bilinear behavior and type of isotropic hardening

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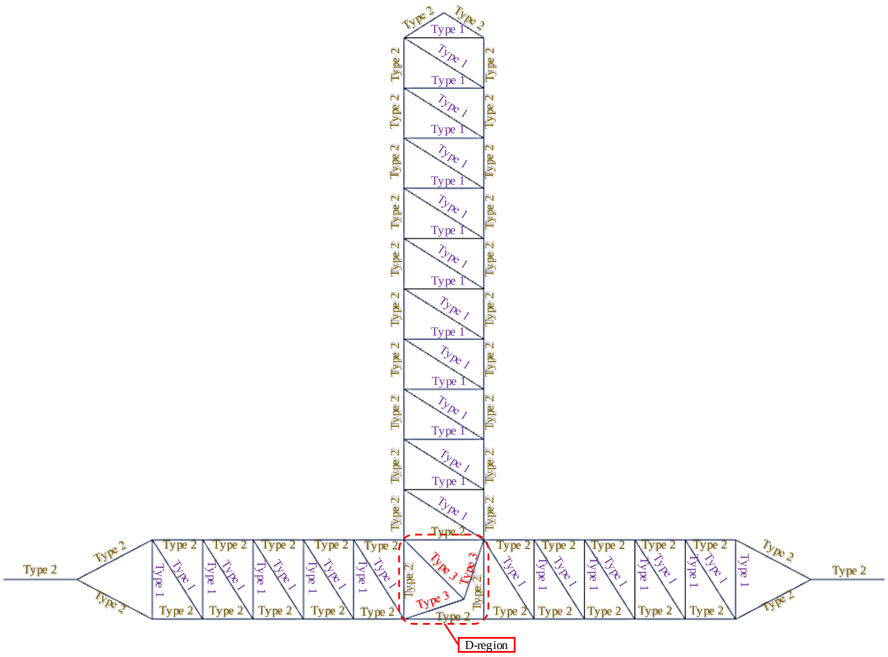

Figure 4: Detail of strut and tie model in ABAQUS software.

5. Nonlinear STM Validation

The Nonlinear STM model was constructed into the nonlinear structural analysis computer program ABAQUS software. Existing material model available from the library in this program were used to represent Concrete and the reinforcing steel. The model is validated by comparing the computed and experimentally measured response of three RC walls that were tested under reversed cyclic loading conditions. The cyclic response was computed using a displacement control algorithm. Stress in strut and tie element at ultimate stage of lateral loading is shown in Figure 5

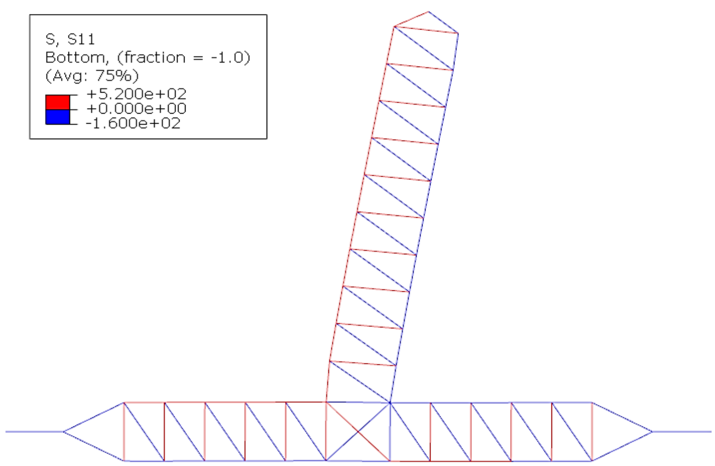

Figure 5: strut and tie stress at ultimate stage of lateral loading.

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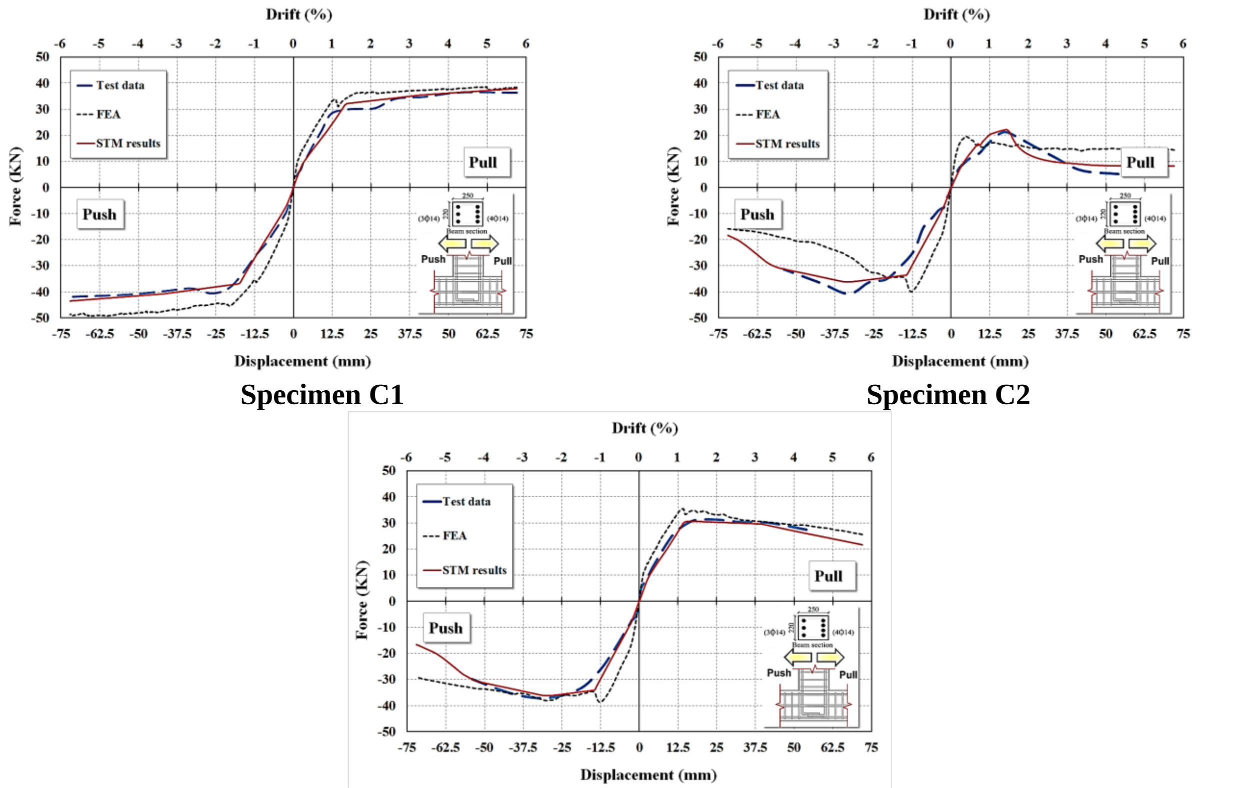
Figure 6 compares the lateral force-lateral displacement response measured during the test with the responses predicted monotonically using nonlinear strut and tie modeling and finite e,emnt modeling approaches. Results show satisfactory agreement between the three sets of data. The elastic and plastic stiffness as well as flexural yield strength of the RC beam-column joint were accurately predicted by the cyclic STM analyses.



Specimen C3

Figure 6: Comparison of load-displacement curve resulted from NSTM approach, FEM and experimental test.

As shown in Figure.. the nonlinear strut and tie modeling can predict the response of sismically and nonseisically detailed beam-column joint with resonable accuracy.

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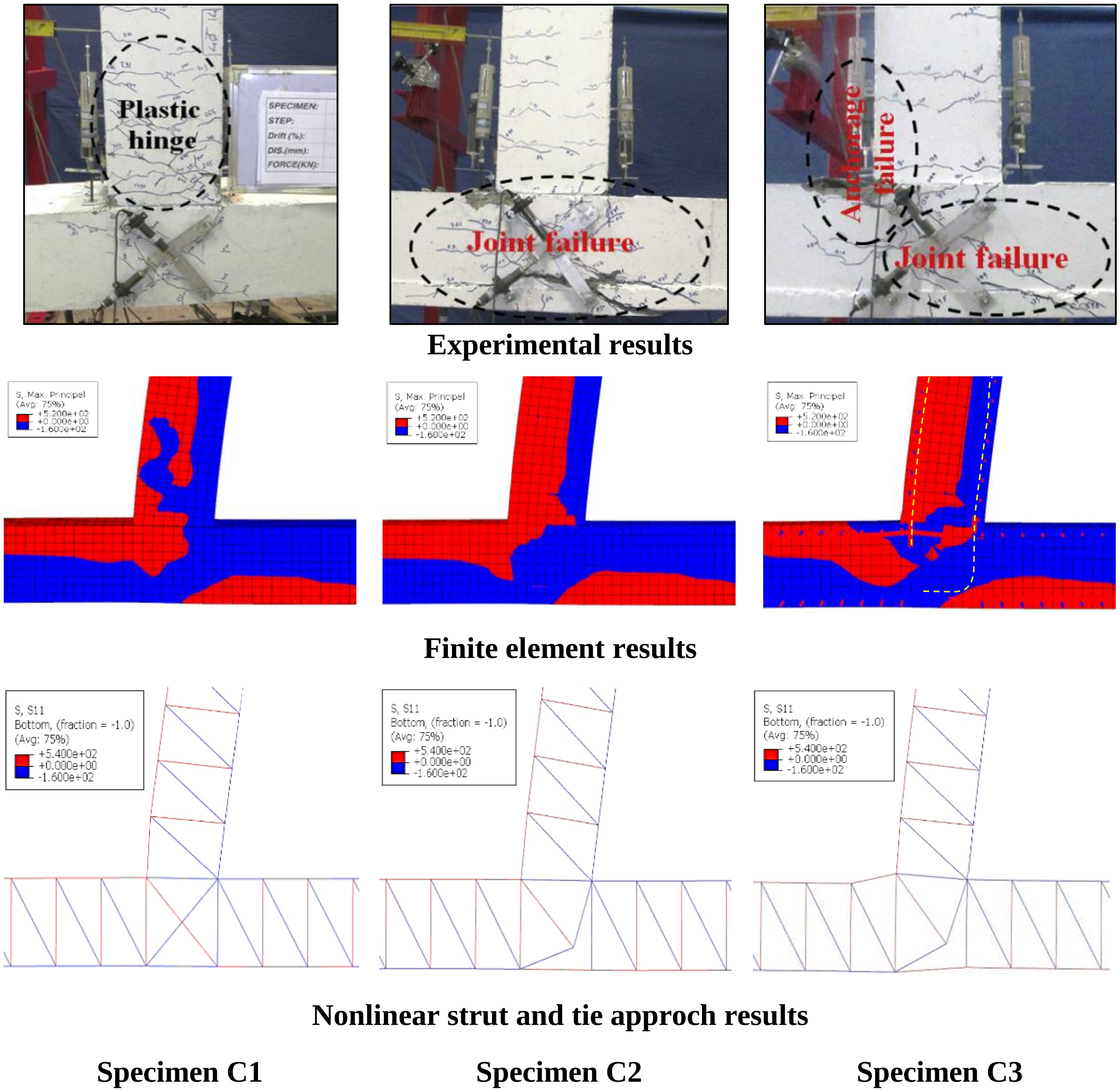

Figure 7: Final failure mode of specimens based on the experimental, FEM and NSTM results.

Based on the Figure 7 in specimen C1 due to seismic details in the joint area, up to 6% drift of lateral loading, the joint beahviour is within elastic range which able to force forming plastic hinge in the face of the column. The force flow in The finite element model represent the correct positions of the compression strut and tensile tie in the STM model and the existence of this similarity and engineering judjement has led to good analytical results. In specimen C2 to drift 6% of lateral loading, the diagonal cracks in the joint area are formed and cause to joint failure before formin plastic hinge in the beam. For modeling of this type of failure mode in the specimen C2 the STM model was revised in the strut in the joint panel. In Specimen C3, the insufficient length of the positive reinforcement of the beam in the joint causes the reinforcement to slip through the concrete, slipping through the concrete and causing the joint to failure. Due to the force path of the finite element model of slip reinforcement, the STM model was simulated by reducing the cross-section of strut associated with the cut armature, which forced the cross-section of the force path to be redistributed from the adjacent struts and increased the amount of stress in the corresponding struts and increased the the plastic area of the main tie creates more strain on the whole model which cause to reduces the load capacity. The analytical result showed that the nonlinear truss model described herein can compute the lateral response of RC beam-column joint of with different reinforcement detailing with a reasonable level of accuracy. As expected, the model computes smaller precracked stiffness in comparision to finite element modelling.

6. Conclusion

•The current research **paper** reported an investigation regarding the application of strut and tie models to model the force-displacement responses of reinforced concrete structures.

•All the force-displacement response envelopes generated using strut and tie models were in satisfactory agreement with experimentally recorded data.

•The formulation procedure developed in the current investigation for strut and tie models was proved to be adequate.

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