



## A NEW MODEL FOR FAILURE MODE OF REINFORCED CONCRETE INTERIOR BEAM COLUMN JOINTS UNDER SEISMIC LOADING

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**Received:** 25 June 2016; **Accepted:** 28 August 2016

### ABSTRACT

The study presented in this paper develops a statistical model which could predict the failure mode of an RC interior beam-column connection under seismic load. A database has been compiled by assembling the details of 150 test specimens loaded to failure under quasi-static cyclic loading, selected from past research. Multinomial logistic regression was employed to develop the model to predict the joint response with three possible outcomes such as shear failure, beam failure and beam-joint failure. Performance analysis of six interior connection specimens, designed to be seismic-resistant with varying aspect ratios, concrete compressive strength, and beam bar yield strength, has validated the statistical model.

**Keywords:** RC interior beam-column connections, probabilistic modelling, cyclic loading, joint failure modes, shear failure.

### 1. INTRODUCTION

The design of reinforced-concrete (RC) moment-resisting frames has become very significant in the earthquake resistant design of structures all over the world. The beam-column joint sub-assembly has been the subject of attention since 1967, when Hansen and Conner [1] conducted the first seismic loading test on it. A considerable amount of experimental and analytical investigations has since been performed with the aim of describing and predicting joint responses in the event of an earthquake. Drawing input from these works, building codes all over the world have undergone a substantial change, with the revision of the existing provisions and the incorporation of new provisions for safe design. Reinforced-concrete moment-resisting frames are designed based on a 'strong column-weak beam' behavior with the intention of inducing a ductile failure, if the situation so demands.

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Despite these precautions, discrepancies have been reported in many cases of joint failure. This can be attributed to the failure in identifying the significance of the role of various design parameters that control joint behavior.

## 2. BACKGROUND: RELATED STUDIES

Investigations of joint behavior have been conducted by researchers worldwide by considering numerous parameters including the geometry, material properties, joint shear strength, reinforcement detailing, and presence of transverse beams, slabs, and eccentric beams. In each of these investigations, observations were drawn from a limited number of test specimens. Hence, it is logical to assume that the results barely reflect the trends in joint behavior. The performance of the joints was evaluated in terms of strength and stiffness by conducting experimental studies in which RC interior beam column joints were tested to failure under quasi-static cyclic lateral loading. As reported by Durrani and Wight [2], the joint shear stress was found to be more critical for specimens without transverse beams. The increase in the amount of joint reinforcement was observed to be more effective in improving the behavior of joints with transverse beams and slabs. The aspect ratio seemingly affects the shear strength, as observed by Shiohara [3]. For interior and exterior beam column connections, a larger aspect ratio corresponds to lower joint shear strength. The author stressed the need to investigate this experimentally as this was an interesting prediction and because prediction of the effect is very critical compared to the other parameters. The concept of quadruple flexural resistance was presented by Shiohara [3], in which the resistance of the joints to the moments from the members framing into the joint is portrayed as four pairs of resultants on diagonal sections. The joint shear failure was redefined as the failure of quadruple flexural resistance. Joh et al. [4], in their study investigating the effect of shear reinforcement on joint strength, reported that heavy joint transverse reinforcement may reduce the slippage of beam bars in the joint and enhance the joint stiffness after cracking. Horizontal hoop reinforcement, provided in the column within the joint region, is reported to confine the concrete and thereby increase its compressive resistance and preserve the integrity of the connection [5, 6]. Leon [7, 8] has conducted detailed studies with respect to the anchorage length of the beam bars and the column depth, and reported that an anchorage length of 20 to 28 times the bar diameter is necessary to anchor bars and to ensure that a weak girder-strong column mechanism can be maintained despite a severe load history. It is observed that, for a connection with large anchorage lengths, only a minimum amount of transverse steel is required in the joint region. Kitayama [9] proposed a 'bond index' to indicate bond deterioration along the beam bars during moment reversals. The value of the bond index increases with the yield strength and the diameter of the beam bars, as well as a reduction in the column width and the concrete compressive strength. Bond deterioration is more likely to occur as the value of the bond index increases. Research studies on the effect of column axial load on the general behavior of joints have produced contradictory results. Some studies have shown that, while an increase in the axial load results in an increase in the energy dissipation capacity of joints with small shear, these results in an unfavorable effect such as the crushing of the concrete

in joints with high shear [10, 11]. In some other studies, the column axial load was reported to be one of the most influential factors affecting the bond performance of joints [12, 13]. A number of studies have underlined the importance of concrete compressive strength in promoting the strength and stiffness of joints [14]. Durrani [15] reported that a higher strength of concrete helps to reduce the stiffness degradation of joints under lateral loading. The compressive stress strain behavior of concrete can be related to the strength of the beam column sub-assembly through principal stresses and strains [16]. As per the studies conducted by Kim (2008) [17] and Murakami (2000) [18], the concrete compressive strength was found to be the most important parameter in determining the reinforced concrete joint shear strength. Kim et al. [17], in their study, developed joint shear strength models using an experimental database in conjunction with the Bayesian parameter estimation method. Of the three models developed, the first model considers all the possible parameters that can influence joint shear strength, while the second model addresses only those parameters left after a step-wise process that systematically identifies and removes the least important parameters affecting the joint shear strength. The third model simplifies the second model such that it can be conveniently applied to practical design. All three models are unbiased and are found to give accurate predictions. Kaveh et al. [18], in their study, presented an optimization problem for accomplishing seismic design of reinforced concrete dual systems. Data bases are initially constructed according to ACI seismic design criteria for beams, columns and shear walls. Formulations for optimum seismic design of moment resisting frames are proposed. The proposed methodology can be considered as a suitable practical approach for optimal seismic design of moment resisting frames.

Despite all these studies, to date a consensus has not been reached regarding the evaluation of the role of certain design parameters in determining the failure modes. Few attempts have been made to quantify the respective role of the design parameters. Statistical modeling provides an ideal analytical alternative in this regard. This method overcomes the limitations of the experimental works by making use of an enormous set of identical test data. This clears the uncertainty surrounding the joint failure behavior and also quantifies the effect of key design variables. In the present study, a database was compiled by assembling the details of 150 test specimens loaded to failure under quasi-static cyclic lateral loading and by maintaining a constant column axial load. Specimens with eccentric beams, out-of-plane geometry, and transverse beams or slabs were excluded from the list. Research papers and reports published in prominent international journals, conferences and proceedings were thoroughly researched to collect the related test data [2-4, 9, 19-32].

### **3. RESEARCH OBJECTIVES AND SIGNIFICANCE**

The main objective of this study was to develop a probabilistic model that could predict the failure mode of an RC interior beam column sub-assembly when loaded laterally. The second objective was to identify the role and significance of various design parameters in determining the failure mode. To achieve these objectives, a database consisting of 150 specimens tested under cyclic loading was compiled. Multinomial logistic regression was then employed to develop a failure mode model to predict the qualitative joint response with

three possible outcomes.

The study presented in this paper developed a statistical model that could predict the failure mode of an RC interior joint under seismic load. The calibrated model classifies the failure mode into three groups: beam failure (BF), beam-joint failure (BJF), and joint failure (JF). The role of the key factors controlling the failure mode was successfully identified and quantitatively assessed. The developed model was validated both theoretically and experimentally by conducting tests on cast specimens. The model results can be effectively used to develop a suitable strengthening technique in the design stage.

#### 4. VARIABLES SELECTED

An extensive literature survey was performed to identify the preliminary variables, which demand close attention. Based on their importance, the key variables selected for this work were classified into two groups: response variables and predictor variables.

##### 4.1 Response variables

The mode of failure was selected as the joint response variable, which is dependent and qualitative in nature. The failure mode has three outcomes, namely, i) BF suggesting beam failure due to beam yielding without any joint shear failure, ii) BJF suggesting beam yielding followed by joint shear failure, and iii) JF suggesting joint shear failure without any beam yielding. The database contains 55 cases of beam failure (BF), 44 cases of beam joint failure (BJF), and 51 cases of joint failure (JF).

##### 4.2 Predictor variables

The design variables selected are independent of each other and are continuous and quantitative in nature. The seven selected variables are explained below.

###### 4.2.1 Aspect ratio ( $A_{spr}$ )

A limited number of research studies have been conducted to identify the significance of the aspect ratio in determining joint behavior [3, 10, 20]. This is the ratio of the depth of a beam to the depth of a column. In the present study, this variable was included to check whether it influences the failure mode.

###### 4.2.2 Ratio of joint transverse reinforcement area ( $A_{shr}$ )

Previous research has shown that the transverse reinforcement in the joint contributes to core confinement [4, 32]. Adequate joint confinement provided by reinforcement is described in ACI 318-11 [33] using the area of the transverse reinforcement. This is used to compute the recommended value of the area of transverse reinforcement.  $A_{shr}$  is then calculated as the ratio of the provided area to the recommended area of the joint transverse reinforcement.

###### 4.2.3 Ratio of anchorage length ( $A_{lr}$ )

Studies on the effect of the anchorage length of the beam bars have shown that the energy dissipation capacity of joints is affected by this factor [7, 8]. ACI 318-11 [34] suggests that,

where the longitudinal beam reinforcement extends through an interior joint, the column depth should not be less than 20 times the diameter of the largest longitudinal beam bar. In the present study,  $A_{lr}$  is calculated as the ratio of the column depth to 20 times the diameter of the largest longitudinal beam bar.

#### 4.2.4 Bond index ( $B_i$ )

This was originally proposed by Kitayama [9] to indicate the bond deterioration along the beam reinforcement. The feasibility of bond degradation may be expressed by the bond index defined as:

$$B_i = \frac{f_y d_b}{2h_c \sqrt{f'_c}} \quad (1)$$

where  $f_y$  is the yield strength of the beam bars,  $d_b$  is the diameter of the beam bars,  $h_c$  is the column depth, and  $f'_c$  is the concrete compressive strength. Bond deterioration is more likely to occur for a higher value of bond index. Previous research has also supported these findings [2, 4, 35, 36]. In the present study, the bond index specified by Eq. (1) is used as one of the design variables.

#### 4.2.5 Concrete compressive strength ( $f'_c$ )

Several studies have underlined the importance of the concrete compressive strength in improving joint shear strength [2, 19, 20, 31, 35, 37-40]. In our analysis, the role of  $f'_c$  in determining the failure mode is being pursued.

#### 4.2.6 Column axial strength ( $f$ )

The role of the column axial load in the joint shear resisting mechanism is a subject of much debate between various schools of thought considering the seismic performance of beam column connections. It has been reported that the column axial load improves the shear resistance of beam column joints by confining the joint core. Some studies have shown that, while an increase in the axial load is favorable to the energy dissipation capacity of joints with a small shear, this result in an unfavorable effect such as the crushing of the concrete in joints subject to high levels of shear [6, 40]. The column axial stress was selected as one of the design variables in this study.

#### 4.2.7 Nominal joint shear stress ( $S_s$ )

Most building codes assume that joint failure occurs when the joint shear reaches the joint shear capacity. Some studies have contradicted this assumption [41]. ACI codes limit the joint shear stress demand to  $1.25\sqrt{f'_c}$  (where  $f'_c$  is the concrete compressive strength in MPa) [5, 34]. Previous research reported that the energy dissipation is relatively high for joints with less shear stress than for joints with a higher shear stress demand [2, 32, 43-46]. Eq. (2) represents the nominal joint shear stress as specified in ACI-352-02 [5], and is considered in this research work to study its influence on the failure mode.

$$S_s = \frac{1}{h_c b_j} \left[ \frac{M_L + M_R}{j h_b} - V_c \right] \quad (2)$$

where  $h_c$  is the column depth;  $b_j$  is the effective joint shear width;  $h_b$  is the depth of the beam;  $V_c$  is the lateral load applied at the column end;  $j h_b$  is the lever arm, and  $M_L$  and  $M_R$  are the flexural strengths of the beam on the left and right of the joint, respectively.

## 5. TRENDS IN THE DATASET

A database has been compiled by assembling the details of 150 test specimens loaded to failure under quasi-static cyclic lateral loading and by maintaining a constant column axial load. The general trends in the dataset are represented in Fig. 1 (a) – (g). Beam yielding is frequently observed when the aspect ratio is around unity. The recommended value of the hoop reinforcement [5] seems to be sufficient only to prevent a joint from experiencing shear failure. The anchorage length should be kept well above the recommended value to allow the joint to develop a beam yielding mechanism. Beam failure mode shares a strong inverse relationship with the bond index. The concrete compressive strength and column axial strength exhibit a mixed relationship with the failure modes. In conjunction with many previous research results [2, 9, 35] the shear stress demand is observed to exhibit a close relationship with the failure modes. Those joints with a high shear stress demand are prone to shear failure. Although most of the design parameters suggest that there is a relationship with the joint response, none were helpful in identifying the significance of their role in determining the likelihood of a failure mode using BF, BJF, or JF mode. Multinomial logistic regression provides an ideal alternative to solve this problem. This identifies the significant parameters related to fixing the joint response modes and permits the quantification of the effects of these parameters. The descriptive statistics of the dataset are represented in Table 1.

Table 1: Descriptive statistics for independent variables in the dataset

Variables	Minimum	Maximum	Mean	SD	COV
$A_{spr}$	1.0	1.5	1.083	0.137	0.126
$A_{shr}$	0.01	26.8	5.99	6.37	1.06
$A_r$	0.72	1.5	1.059	0.179	0.169
$B_i$	0.92	4.28	1.922	0.759	0.395
$f'_c$ (MPa)	21.26	117.77	50.825	25.15	0.494
$f$ (MPa)	0.89	23.54	7.381	5.685	0.770
$S_s$ (MPa)	2.76	31.90	9.995	6.308	0.631

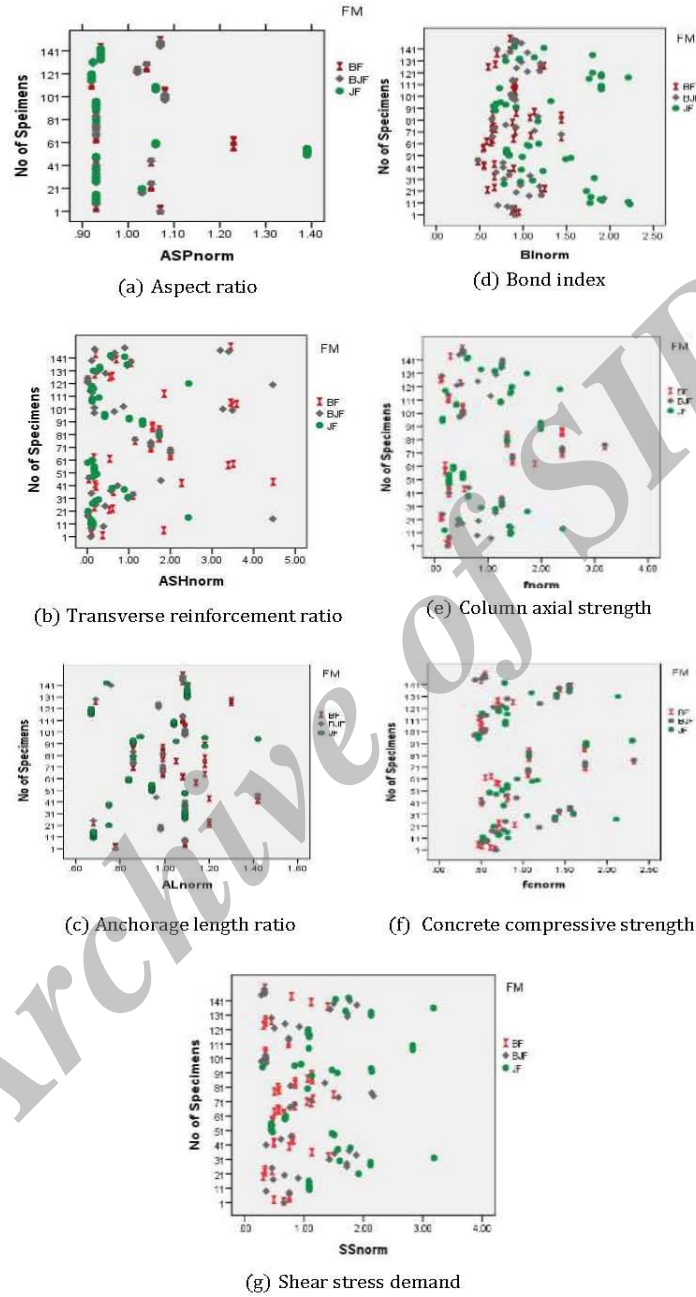


Figure 1. Scatter plot of predictor variables

## 6. MULTINOMIAL LOGISTIC REGRESSION

Multinomial logistic regression is an established technique that is used to predict the probability of category membership on a dependent variable based on multiple independent predictor variables [47-52]. It allows the predictors to be continuous. It does not make use of the assumptions of normality, linearity, or homoscedasticity. Each of the variable values in the dataset is normalized with their respective mean value for avoiding the problem of multicollinearity. This method uses the maximum likelihood estimation method to evaluate the probability of the categorical membership of the dependent variable. One of the categories to which the response variable belongs is selected as the reference category. The log-odds of all other outcomes relative to the reference category are then calculated and expressed as a linear function of the predictor variables. The log-odds of each outcome are expressed as

$$\{P_{ij}\} = \left\{ \log \left( \frac{\pi_{ij}}{\pi_{i1}} \right) \right\} = \{a_j\} + [\beta_{ji}]\{X_i\} \quad (3)$$

where  $a_j$  is a constant;  $\beta_{ji}$  is a matrix of regression coefficients;  $X_i$  is the independent variable;  $i$  changes from one to the total number of predictors;  $j$  changes from 1 to  $(j-1)$ ; and  $j$  represents the number of response variable categories. This generates  $(j-1)$  equations. In terms of the original probabilities  $\pi_{ij}$ , rather than representing them by log-odds and adopting the convention that  $P_{ij} = 0$ , the Eq. (3) can be written as

$$\pi_{ij} = \frac{e^{P_{ij}}}{\sum_1^j e^{P_{ik}}} \quad (4)$$

where  $\pi_{ij}$  is the probability that the response variable belongs to category  $j$ . Eq. (4) will automatically yield probabilities that add up to one for each  $i$ .

### 6.1 Analytical model

In the present study, the dependent variable failure mode has three categories, i.e., BF, BJF, and JF, as explained previously. BF, which is the beam failure without any joint shear failure, is selected as the reference category and is referred to as event 1. BJF, the beam yielding in conjunction with joint shear failure, is represented as event 2. JF, which is the joint shear failure without any beam yielding, is considered as event 3. In this analysis, two comparisons are made. In the first comparison, the chance occurrence of event 2 is compared to that of event 1. Similarly, in the second comparison, the chance occurrence of event 3 is compared to that of event 1. Eq. (5) and Eq. (6) represent the likelihood of observing BJF and JF mode by defining the log-odd ratios for events 2 and 3, respectively.

$$\log \left( \frac{P(E2)}{P(E1)} \right) = a_1 + \sum_1^n \beta_i X_i \quad (5)$$



$$\log\left(\frac{P(E3)}{P(E1)}\right) = a_2 + \sum_1^n \beta_i X_i \tag{6}$$

where n is the number of independent variables or covariates for which the relationship with the response variable has proven to be statistically significant at a level of 0.05. The covariates and analysis results are presented in Table 2.

Table 2: Multinomial logit model

Comparison	Covariate ( $X_i$ )	Coefficient ( $\beta_i$ )	Odds ratio Exp ( $\beta_i$ )	Standard Error	p value	T statistic	Intercept
Equation (5)	$\frac{S_s}{S_s\ mean}$	2.78	16.11	1.112	0.012	2.5	-0.46
	$\frac{A_{spr}}{A_{spr\ mean}}$	1.064	2.89	1.012	0.003	1.05	
	$\frac{A_{shr}}{A_{shr\ mean}}$	-0.893	0.41	0.422	0.034	-2.116	
Equation (6)	$\frac{B_i}{B_i\ mean}$	4.412	82.46	1.638	0.007	2.69	-17.8
	$\frac{S_s}{S_s\ mean}$	4.508	90.72	1.252	0.000	3.6	

6.2 Validation of model

The IBM SPSS 21 software package [53] was used to obtain the multinomial logistic regression coefficients.

6.2.1 Goodness of fit

There are various indices for assessing the intercept-only model (null model) and the final model, which includes all of the predictors and the intercept (full model). Akaike information criterion (AIC) and Bayesian information criterion (BIC) are two information theory based model fit statistics. Lower values of each indicate a better-fit model. In this analysis, both of these indices showed lower values, suggesting a better fit for the analytical model. The -2 Log Likelihood (-2LL) is a likelihood ratio test, which represents the unexplained variance in the response variable. The smaller value indicates a better fit. The -2LL values obtained for the null and full models are 239.35 and 161.87, respectively; thus, they indicate a better fit. The overall test of relationships among the predictor variables and response variable is based on the reduction in the likelihood values for a model that does not contain any predictor variables and a model that contains the predictor variables. The difference in likelihood is assumed to follow a chi-square distribution. In this analysis, the probability of the model chi-square (77.4) was 0.000, which is less than or equal to the level of significance of 0.05. This supported the existence of a relationship between the independent variables and dependent variable.

### 6.2.2 Classification accuracy

Normally, a benchmark is used to characterize a multinomial logistic regression model as being useful, specifically, a 25% improvement over the rate of accuracy achievable by chance alone. The estimate of the by-chance accuracy that is used is proportional to the by-chance accuracy rate, computed by summing the squared percentages of cases in each response variable group. In this analysis, the proportional by chance accuracy criteria is 42%. The classification accuracy rate for the model was 79%, which is greater than the proportional by chance accuracy criteria. The developed model satisfies the criteria of the classification accuracy rate [47, 50-52].

### 6.2.3 Parameter estimates

Table 2 represents the logistic coefficient  $\beta$  for each independent variable. The logistic coefficient is the expected amount of change in the logit for each one-unit change in the predictor variable. The logit is what is being predicted. The predictors that increase the logit will display an  $\text{Exp}(\beta)$  greater than 1.0; those predictors that do not have an effect on the logit will display an  $\text{Exp}(\beta)$  of 1.0; and the predictors that decrease the logit will have an  $\text{Exp}(\beta)$  of less than 1.0. The Wald test evaluates whether the independent variable is statistically significant in differentiating between the two groups in each of the comparisons. The computed t statistic and the associated p values proved that the statistical significance of the variables is at the 0.05 level [48, 51-52].

### 6.2.4 Predictive efficiency of statistical model

The predictive efficiency of the model was tested using the dataset. The results are presented in Table 3. The model predicts the response outcomes with an adequate level of accuracy.

Table 3: Classification by model

Observed Failure Mode	Predicted Failure Mode			Percent Correct
	BF	BJF	JF	
BF	42	12	1	76.36 %
BJF	8	33	3	75 %
JF	2	6	43	84.31 %
Overall Percent				78.56 %

### 6.3 Experimental validation of model

The statistical model has been validated by an experimental program designed in accordance with the model parameters. Six interior joint specimens designed and detailed as per IS 13920 (1993) [54], scaled down to 1/3<sup>rd</sup> of its original size were cast and tested under cyclic lateral loading until failure. The modes of failure observed for the specimens were compared with the predicted failure modes by the model.

### 6.3.1 Specimen details

Seismically detailed interior beam-column connection specimens, having a height of 1.3 m and width of 1.5 m, were designated X1 to X6. The mix design was conducted as per IS 10262 (2009) [55]. Fig. 2 shows the detailing pattern and dimensions of the specimens. Three different concrete compressive strengths and aspect ratios were selected for the analysis. High-yield-strength deformed (HYSD) bars having yield strength of 500 MPa were used as the longitudinal bars in the columns as well as in the beams. Specimen X6 consisted of HYSD bars having yield strength of 415 MPa as the beam longitudinal bars.

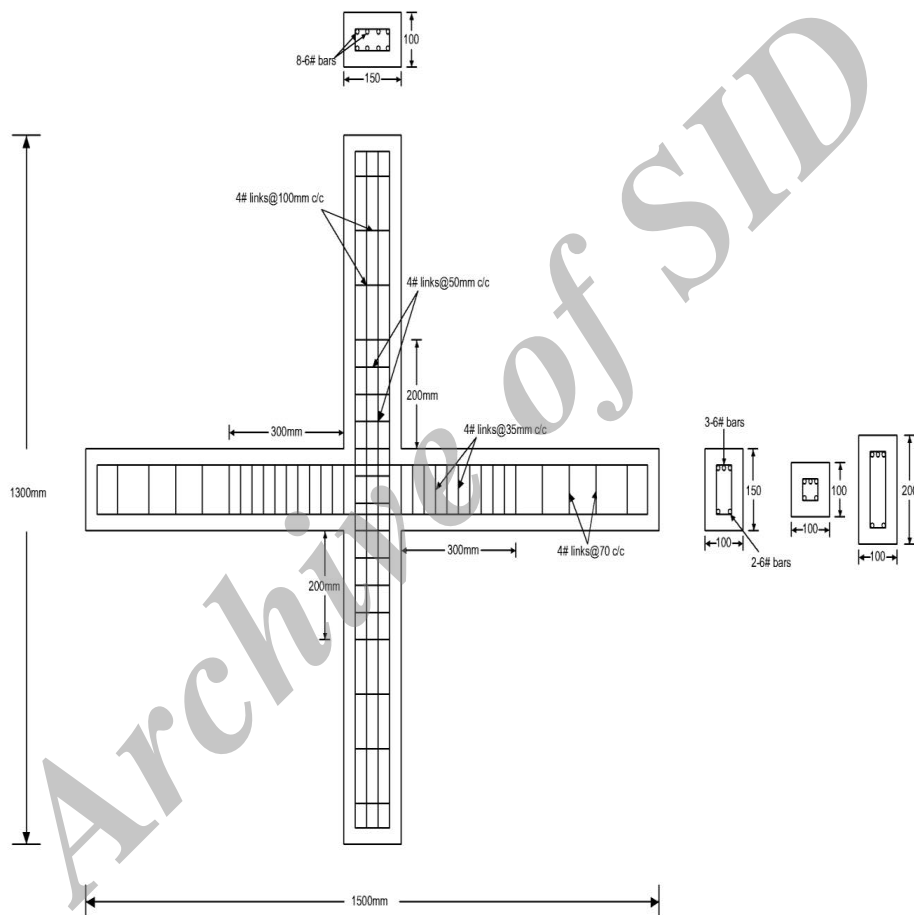


Figure 2. Details and dimensions of specimens

The columns in all the specimens were reinforced with eight HYSD bars having a diameter of 6 mm and yield strength of 500 MPa, equally distributed along the two longer sides, as shown in Fig. 2. The beams were provided with five bars having a diameter of 6 mm, i.e. three at the top and two at the bottom. Further, 6-mm hoops were used as transverse reinforcements in both the beams and the columns. The material and geometrical characteristics of the specimens are summarized in Table 4.

Table 4: Geometric and material characteristics of specimens

Specimen details	X1	X2	X3	X4	X5	X6	
	Column						
	150×100						
Cross section (mm)	Beam	100×150	100×100	100×200	100×150	100×150	100×150
$h_c$ (mm)		150	150	150	150	150	150
$b_j$ (mm)		100	100	100	100	100	100
$h_b$ (mm)		150	100	200	150	150	150
$f_c$ †(MPa)		40.71	40.18	39.33	33.78	44.22	40.22
$f_c$ ‡(MPa)		33.29	33.12	32.22	26.04	39.18	32.27
Beam longitudinal reinforcement $A_{sb}$		5 no 6-mm bars $f_y=500$ MPa					5 no 6-mm bars $f_y=415$ MPa
Column longitudinal reinforcement $A_{sc}$		8 no 6-mm bars $f_y=500$ MPa					
Transverse reinforcement $A_{sh}$		6 mm hoops $f_y=500$ MPa					

† Concrete cube compressive strength on day of testing

‡ Concrete cylinder compressive strength on day of testing

### 6.2.2 Materials

Ordinary Portland cement (53 grade), M-sand passing through a 4.75-mm IS sieve (fineness modulus, 2.5; specific gravity, 2.5), and crushed stone with a maximum size of 12 mm (specific gravity, 2.76) and 6 mm (specific gravity, 2.74) were used for this investigation.

### 6.2.3 Test procedure and instrumentation

The specimens were tested in an upright position in a steel loading frame (capacity, 200 t). An axial compressive load of 10% of the axial capacity of the column was applied to the column by means of a hydraulic jack (capacity, 30 t). The bottom of the column of the beam-column connection was pinned to a strong floor. The beam ends were subjected to quasi-static cyclic loading. The loading was performed in displacement control mode. The test setup is shown in Fig. 3. The beams in the beam-column connections were loaded up to a certain magnitude of displacement and then unloaded in the opposite direction and reloaded to obtain a full cycle of reverse loading. Each loading cycle was repeated twice; after each cycle, the magnitude of the displacement was increased. The process was continued until the specimen reached its maximum capacity. Thereafter, the loading was applied without repetition of the loading cycle until failure. Fig. 4 shows the cyclic loading history. In each loading stage, the deflections at the tips of the beams were measured using two linear variable differential transformers (LVDTs) having a minimum count of 0.01 mm and gauge length of 200 mm.

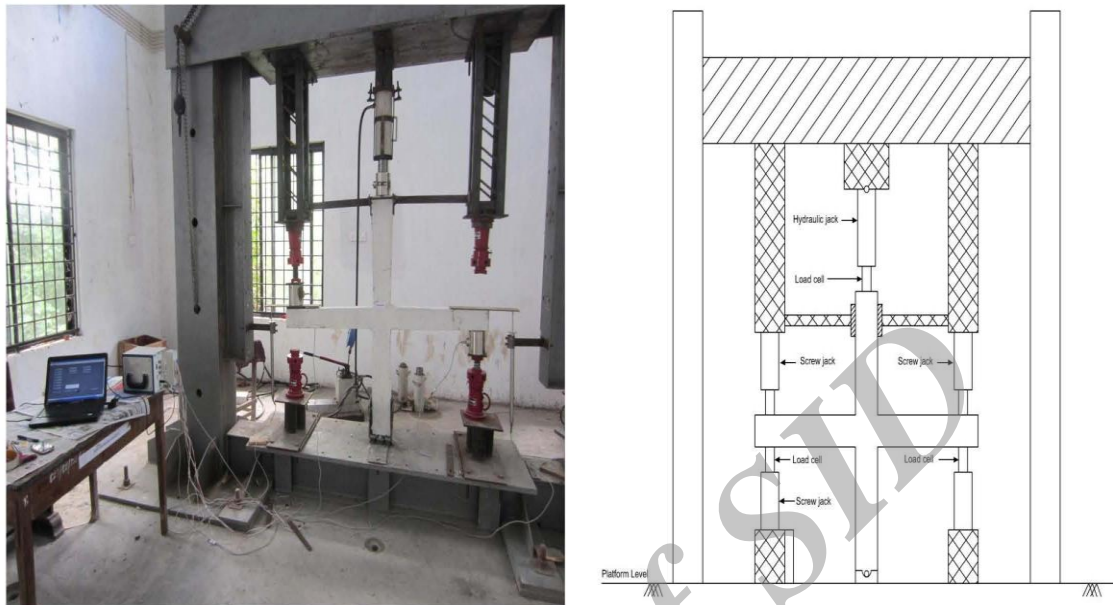


Figure 3. Test setup

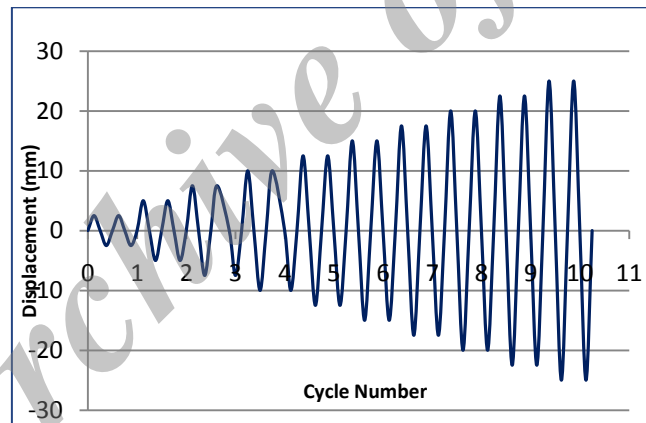


Figure 4. Cyclic loading histories

#### 6.3.4 Test results

The damage pattern observed for each specimen is illustrated in Fig. 5. The observed failure patterns corresponded to the failure modes as predicted by the logit model. All the specimens were observed to exhibit the failure mode predicted by the model. Specimen X1 exhibited beam joint failure mode, specimens X2 and X4 failed in joint shear, and specimens X3, X5, and X6 exhibited ductile beam failure. Therefore, it is assumed that the model results converge to the actual results and that the predictability of the model is very good. The test results are listed in Table 5.



Figure 5. Damage patterns of test specimens

Table 5: Validation test data

Specimen details	X1	X2	X3	X4	X5	X6
Joint shear strength $\tau_{ja}$ (MPa)	7.23	8.01	6.59	6.13	8.09	7.37
Bond index $B_f$ ( $\sqrt{\text{MPa}}$ )	1.73	1.74	1.76	1.96	1.6	1.45
Joint transverse reinforcement ratio $A_{shr}$	1.56	1.58	1.61	1.88	1.43	1.31
Aspect ratio $A_{spr}$	1.0	0.67	1.33	1.0	1.0	1.0
FM actual	BJF	BF	JF	JF	BF	BF
FM predicted	BJF	BF	JF	JF	BF	BF

## 7. DISCUSSION

The multinomial logit model indicates the variables that play significant roles in determining the likelihood of each failure mode as shear strength, bond index, aspect ratio, and the ratio of the joint transverse steel. The design variables, including the concrete compressive strength, column axial load, and anchorage length are insignificant in determining the failure modes. The p values associated with these variables failed to assume the statistical importance by not qualifying at the 0.05 level.

### 7.1 Effect of aspect ratio

The magnitude of the logistic coefficient  $\beta$  indicates that the aspect ratio is one variable that is important in differentiating the joint shear failure (JF) from the beam failure (BF). As the value of  $A_{spr}$  increases, the likelihood of joint shear failure increases relative to beam

failure. The magnitude of the logistic coefficient  $\beta$  indicates that the aspect ratio is one variable that is important in differentiating the joint shear failure (JF) from the beam failure (BF). As the value of  $A_{spr}$  increases, the likelihood of joint shear failure increases relative to beam failure.

#### 7.2 Effect of joint transverse reinforcement

The negative value obtained for regression coefficient  $\beta$  indicates that, as the amount of transverse reinforcement increases, the likelihood of joint shear failure decreases relative to that of beam failure. It is found to play an insignificant role in distinguishing the beam joint failure from beam failure.

#### 7.3 Effect of bond index

A very high odd ratio associated with the bond index proved its prime importance in determining the nature of the failure mode. As the value of the bond index increases, the joint specimen has a very high likelihood of failing in joint shear failure mode (JF), relative to a beam failure (BF). It must also be noted that the parameter bond index does not exert any influence on differentiating between BJF and BF modes.

#### 7.4 Effect of shear stress

Of all the independent design variables considered, the most influential one was found to be the joint shear demand. This variable enables differentiation not only between JF and BF mode but also between BJF and BF mode. Similar to the bond index, the odd ratio associated with the shear stress exhibits a very high positive value, thus indicating a rapid increase in the likelihood of the occurrence of joint shear failure (JF) mode compared to beam failure (BF) mode as the shear demand increases. This is the only predictor variable that was able to distinguish the BJF mode from the BF mode. Relatively high values of  $\beta$  and  $\text{Exp}(\beta)$  indicate that, by keeping all of the other parameters constant, the likelihood of the occurrence of BJF mode increases with an increase in the shear stress. A multinomial logit model capable of predicting the interior beam column joint failure modes with three possible outcomes is developed. The following conclusions can be drawn from the results of this study.

- 1) The two most influential variables determining the type of failure of interior beam column joints are identified as the joint shear stress and the bond index. The other relatively less influential variables are the aspect ratio and the area of joint transverse reinforcement.
- 2) Shear failure mode JF is predominantly the output of the collective role played by the bond index and shear stress. A very high value of both ultimately leads to a brittle failure such as joint shear failure. A reduction in the amount of transverse reinforcement and a high aspect ratio are catalysts leading to a further increase in the speed of the process.
- 3) Beam failure (BF) occurs when there is a combination of factors such as a very low value of bond index, a major reduction in joint shear stress demand and high value for the amount of joint transverse reinforcement. All these factors together lead to a perfect ductile response such as beam failure.

- 4) The shear stress plays the role of differentiating beam joint failure from beam failure. The shear stress demand is moderate in specimens that fail in the BJT mode compared to that of the specimens that fail during beam flexure. It is reasonable to assume that a very low value of bond index, a high amount of transverse reinforcement, and a moderate value of joint shear stress with together result in beam yielding followed by joint shear failure, specified as BJT mode.

The multinomial logit model is consistent with the observed behavior of the beam-column joint sub-assemblages under seismic lateral loading. The model demonstrated how it predicts the failure mode and how it can account for the effect of key variables in differentiating the failure mode.

**Acknowledgements:** The authors wish to gratefully acknowledge the Government of Kerala (Quality Improvement Programme) for financially supporting this study and Editage (www.editage.com) for providing the language editing service.

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