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SEISMIC EVALUATION OF RC FRAMED BUILDING USING SHEAR FAILURE MODEL

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ABSTRACT

Prediction of nonlinear shear hinge parameters in RC members is difficult because it involves a number of parameters like shear capacity, shear displacement, shear stiffness. As shear failure are brittle in nature, designer must ensure that shear failure can never occur. Designer has to design the sections such that flexural failure precedes the shear failure. Also design code does not permit shear failure. However, past earthquakes reveal that majority of the reinforced concrete (RC) structures failed due to shear. Indian construction practice does not guaranty safety against shear. Therefore accurate modeling of shear failure is almost certain for seismic evaluation of RC framed building. Therefore, the primary objective of the present work is to develop nonlinear force deformation model for reinforced concrete section for shear and demonstrate the importance of modeling shear hinge in seismic evaluation of RC framed building. It is found that equations given in Indian Standard IS-456: 2000 and American Standard ACI-318: 2008 represent good estimate of ultimate strength. Two building models, one with shear hinge and other without shear hinges, are analyzed using nonlinear static analysis. The results obtained here show that the presence of shear hinge can correctly reveal the non-ductile failure mode of the building.

***Keywords**:* shear hinge, shear capacity, shear displacement, shear stiffness, and reinforced concrete.

I. INTRODUCTION

The problem of shear is not yet fully understood due to involvement of number of parameters. In earthquake resistance structure heavy emphasis is placed on ductility. Hence designer must ensure that shear failure can never occur as it is a brittle mode of failure. Designer has to design the sections such that flexural failure antedates the shear failure. Also, shear design is major important factor in concrete structure since strength of concrete in tension is lower than its strength in compressions. However, past earthquakes reveal that majority of the reinforced concrete structures failed due to shear. Indian construction practice does not guaranty safety against shear. A nonlinear analysis like this can predict the failure mode, maximum force and deformation capacity of the structure. But to do an accurate analysis nonlinear modeling of frame sections for flexure and shear is very important. However, the nonlinear modeling of RC sections in shear is not well understood. The current industry practice is to do nonlinear analysis for flexure only. Therefore, the primary objective of the present work is to develop nonlinear force-deformation model for RC rectangular section for shear (Fig.1). Also it is important to check how nonlinear modeling of shear alters the seismic behavior of RC framed building.

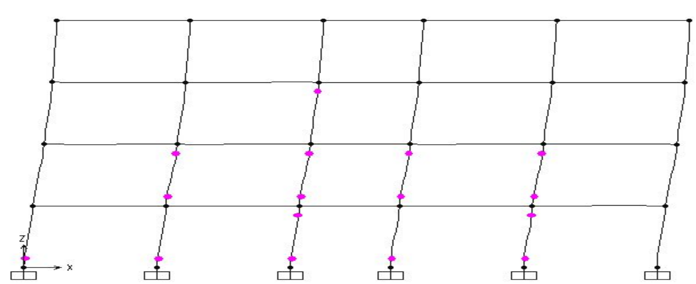

Fig1. Deformed shape of a nonlinear building model under lateral load

CODE PROVISIONS

Major international design codes with regard to the shear provision in RC section. This includes Indian Standard IS 456: 2000, British standard BS 8110:1997 (Part 1), American Standard ACI 318: 2008 and FEMA 356: 2000. The shear capacity of a section is the maximum amount of shear the beam can withstand before failure. International design codes recommend procedures to calculate shear strength of rectangular and circular RC sections with transverse reinforcement.

However, all the design codes are silent about the maximum shear displacement capacity of RC sections. Shear strength estimation procedures as per few major international codes are discussed as follows.

Indian Standard (Is 456: 2000)

Indian standard IS 456: 2000 as per Clause 40.1, specify the nominal shear stress by following equations.

$$\tau_v = \frac{V_u}{bd}$$

Shear carried by concrete is given by

$$V_u = \delta \tau_c bd$$

Where

$$\delta = 1 + \frac{3P_u}{A_g f_{ck}} \leq 1.5, \text{ and } \tau_c = \frac{0.85\sqrt{0.8 f_{ck}}\left(\sqrt{1+5\beta}-1\right)}{6\beta}$$

$$\beta = \frac{0.116 f_{ck} bd}{100 A_{st}} \geq 1.0$$

As per clause 40.2.2, for member subjected to axial compression Pu **,** the design shear strength of concrete, given in Table 19 shall be multiplied by the following factor :

$$\delta = 1 + \frac{3P_u}{A_g f_{ck}} \leq 1.5$$

The design shear strength of concrete *(*τ_c *)* in beam without shear reinforcements is given in Table 19. τ_c Depend upon percentage of steel p_t which is given by

$$p_t = \frac{100 A_{st}}{bd}$$

If τ_v exceeds τ_c given in Table *19 ,* Shear reinforcement shall be provided in any of the following forms:

- Vertical stirrups
- Bent-up bars along with stirrups
- Inclined stirrups

Contribution of web reinforcement in shear strength given in *IS-456: 2000* represent ultimate strength of the stirrups given by

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$V_s = 0.87 f_y A_{sv} \frac{d}{s_v}$ for vertical stirrups

$V_s = 0.87 f_y A_{sv} \sin\alpha$ for bent upbars

$V_s = 0.87 f_y A_{sv} \frac{d}{s_v} (\sin\alpha + \cos\alpha)$ for inclined stirrups

British Standard (Bs 8110: 1997, Part 1)
British standard BS 8110: PART 1 as per clause *3.4.5.2*, specify the nominal shear stress by following equations.

$$v = \frac{V}{b_v d}$$

Where *bv* is the breadth of the section. For a flanged beam width is taken as the width of the rib below the flange. *V* is the design shear force due to ultimate loads and *d* is the effective depth. The code gives in Table *3.9* the design concrete shear stress v_c which is used to determine the shear capacity of the concrete alone. Values of v_c depend on the percentage of steel in the member, the depth and the concrete grade. The design concrete shear stress is given by

$$V_c = \left[\frac{0.79}{\gamma_m}\right] \times \left[\frac{100 A_s}{bd}\right]^{\frac{1}{3}} \times \left[\frac{400}{d}\right]^{\frac{1}{4}} \times \left[\frac{f_{cu}}{25}\right]^{\frac{1}{3}} for\ \frac{a}{d} > 2$$

Where

$$\frac{100 A_s}{bd} \leq 3, \frac{400}{d} \geq 1 \quad \gamma_m = 1.25 \& \ f_{cu} \leq 40MPa$$

American Concrete Institute (Aci318: 2008)
ACI 318: 2008, specify that the shear strength is based on an average shear stress on the full effective cross section *bw d.* For a member without shear reinforcement, shear is assumed to be carried by the concrete web and member with shear reinforcement, a portion of the shear strength is assumed to be provided by the concrete and the remainder by the shear reinforcement. As per clause *11.2*,

$$V_y = V_c + V_s$$

$$V_c = \delta \times (0.17\sqrt{f_c'}) \times bd \left[\text{ where }, \delta = 1 + \frac{P_u}{14A_g}\right]$$

$$V_s = \frac{A_{sv} \times f_{yh} \times d}{S_v} \text{ for vertical stirrups}$$

$$V_s = \frac{A_{sv} \times f_{yh} \times d}{S_v} (\sin\alpha + \cos\alpha) \text{ for inclined stirrups}$$

Federal Emergency Management Agency (Fema 356)
FEMA-*356* does not consider contribution of concrete in shear strength calculation for beam under earthquake loading. FEMA-*356* consider ultimate shear strength carried by the web reinforcement (= strength of the beam) as *1.05* times the yield strength. But there is no engineering background for this consideration.

II. SHEAR CAPACITY MODEL

The shear capacity of a section is the maximum amount of shear the section can withstand before failure. Based on theoretical concept and experimental data researchers developed many equations to predict shear capacity but no unique solutions are available. Three parameters: cylindrical compressive strength (f_c) longitudinal reinforcement ratio (ρ) and shear span-to-depth ratio (a/d) are considered for developing equations for estimating shear strength of RC section without web reinforcement.

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Factors affecting shear capacity of beam

There are several parameters that affect the shear capacity of RC sections without web reinforcement. Following is a list of important parameters that can influence shear capacity of RC section considerably:

- Shear span to depth ratio (a/d)
- Tension steel ratio (ρ)
- Compressive strength of Concrete (f_c)
- Size of coarse aggregate
- Density of concrete
- Size of beam
- Tensile strength of concrete
- Support conditions
- Clear span to depth ratio (L/d)
- Number of layers of tension reinforcement
- Grade of tension reinforcement
- End anchorage of tension reinforcement.

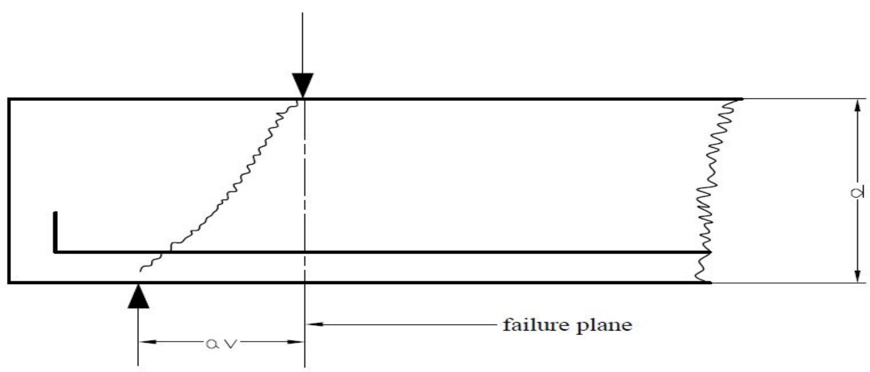

Fig2. Shear capacity near support

Modes Of Failure In Shear

Modes of shear failure for beam without web reinforcement depend on the shear span. Shear failure is generally classified based on shear span into three types as follows:

i) Diagonal tension failure (a > 2d)

ii) Diagonal compression failure (d ≤ a ≤ 2d)

iii) Splitting or true shear failure (a < d)

Example Of Shear Strength Estimation

To compare the shear capacity equations available in literature a test beam section is considered and shear capacity for this beam section is calculated using all the equation presented above. The details of the test section are given below. Fig.3 presents a sketch of the test beam considered for the comparison.

Details:

• Type of the beam: Simply supported beam subjected to one point load.
• Beam size = 150 × 250 mm with cover 25 mm.
• Span = 3 m.
• Shear span-to-depth ratio = 3.6
• Top reinforcement = 3 number of 12 mm bars (3Y12)
• Bottom reinforcement = 3 number of 16 mm bars (3Y16)

- Web reinforcement = 2 legged 8 mm stirrups at 150 mm c/c
- Shear span = 810 mm.
- Maximum aggregate size = 40 mm.
- Grade of Materials = M 20 grade of concrete and Fe 415 grade of reinforcing steel

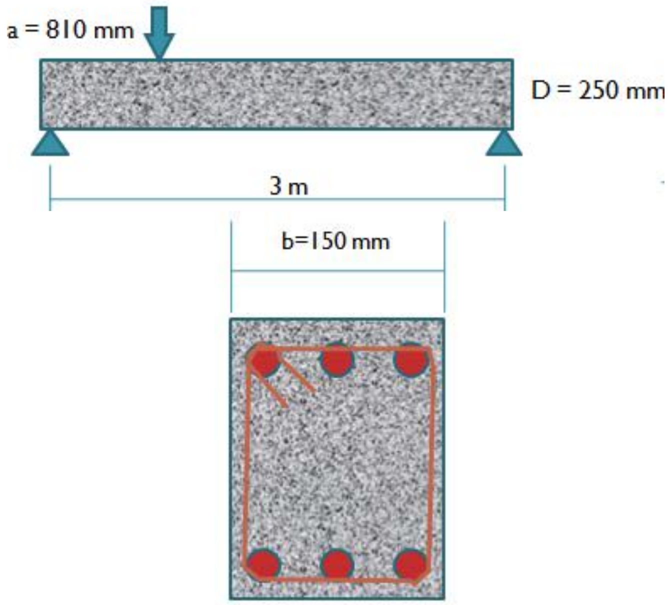

Fig. 3 Test beam section considered for the comparison.

Table 1. Ultimate shear strength (KN) of beam

Methods	Vc (kN)	Vs (kN)	Vy (kN)	Vu (kN)
BS 8110 : 1997	27.71	-	-	-
IS 456:2000	30.10	54.42	-	84.52
ACI 318: 2008	22.95	62.55	-	85.50
FEMA - 356	0	Vs,y	Vy=Vs,y	1.05Vy

III. SHEAR DISPLACEMENT MODEL

The following model are developed to calculate the shear displacement at the maximum shear strength.

Park and Paulay (1975)

The theory of calculating ultimate shear displacement is based on truss analogy. This was actually proposed for concrete beams but has been commonly used for columns. A Concrete beam subjected to shear is modeled as shown in Fig.4

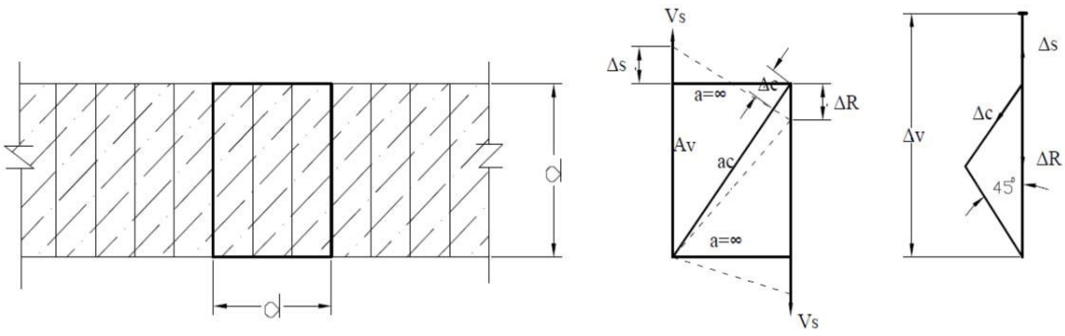

Fig4 Shear displacement for beam (Park and Paulay 1975)

From geometry, shear displacement as, $\Delta_v = \Delta_s + \sqrt{2\Delta c}$

Where

$\Delta_c = \frac{2\sqrt{2}V_s}{E_c b_w}$ =Shortening of concrete (*i.e*. compression of struts)

$\Delta_s = \frac{V_s}{E_s A_v}$ =Elongations of stirrups

Expressing the displacements in terms of the shear force resisted by stirrups *Vs*, Then shear distortion per unit length θ_v as

$$\theta_v = \frac{V_s}{E_s b_w d}\left[\frac{1}{\rho_v} + 4\eta\right]$$

Where E_s = Modulus of elasticity for steel,

$\eta = \frac{E_s}{E_c}$ = Modular ratio

b_w= Width of beam web

d= Effective depth

$\rho_v = \frac{A_v}{s b_w}$ =Transverse reinforcement ratio

It does not take into account the effect of axial load thus its use to predict the shear displacement of compression members should be avoided.

IV. MATERIAL

The material properties of any member consists of its mass, unit weight ,modulus of elasticity, poisson's ratio, shear modulus and coefficient of thermal expansions.The material grades used for frame model are presented in Table 2

Material	Grade
Concrete	M 20
Reinforcing steel	Fe 415

Elastic material properties of these materials are taken as per Indian Standard IS 456:2000. The short-term modulus of elasticity (*Ec*) of concrete is taken as: $E_c = 5000\sqrt{f_{ck}}$ MPa

fck is the characteristic compressive strength of concrete cube in MPa at 28-day (25 MPa in this case). For the steel rebar, yield stress (*fy*) and modulus of elasticity (*Es*) is taken as per IS 456 (2000)

Stress-Strain Characteristics for Concrete

The stress-strain curve of concrete in compression forms the basis for analysis of any reinforced concrete section. The characteristic and design stress-strain curves specified in most of design codes (IS 456: 2000, BS 8110) do not truly reflect the actual stress-strain behaviour in the post-peak region, as it assumes a constant stress in this region (strains between 0.002 and 0.0035). In reality, as evidenced by experimental testing, the post-peak behaviour is characterised by a descending branch, which is attributed to 'softening' and micro-cracking in the concrete. However, the stress-strain relation specified in ACI 318M-02 consider some of the important features from actual behaviour.

Stress-Strain Characteristics for Reinforcing Steel

The constitutive relation for reinforcing steel given in IS456(2000) is well accepted in literature and hence considered for the present study. The 'characteristic' and 'design' stress-strain curves specified by the Code for Fe-415 grade of reinforcing steel (in tension or compression) are shown in Fig. 5.11.

Assumptions

i. The strain is linear across the depth of the section ('plane sections remain plane').
ii. The tensile strength of the concrete is ignored.
iii. The concrete spalls off at a strain of 0.0035.
iv. The initial tangent modulus of the concrete, *Ec* is adopted from IS 456 (2000), as 5000 *ck f* .
v. In determining the location of the neutral axis, convergence is assumed to be reached within an acceptable tolerance of 1%

V. MODELLING OF SHEAR HINGES

When there is no prior failure in shear, flexural plastic hinges will develop along with the predicted values of ultimate moment capacity. Design codes prescribe specifications (e.g.ductile detailing requirement of IS 13920: 1993) for adequate shear reinforcement,corresponding to the ultimate moment capacity level. Therefore, it is obvious for a code designed building to fail in flexure and not in shear. There are a lot of buildings existing those are not detailed with IS 13920: 1993. Also, poor construction practise may lead to shear failure in framed building in the event of severe earthquakes. Shear failure mostly occur in beams and columns owing to inadequate shear design. In non-linear analysis, this can be modelled by providing 'shear hinges'. These hinges located at the same points as the flexural hinges near the beam column joints. If the shear hinge mechanism occurred before the formation of flexural hinge, the moment demand gets automatically restricted because of this flexural hinge may not develop. As per clause 40.4 of IS 456: 2000, Shear resistance carried by shear reinforcement (*Vsy*) is

$$V_s = 0.87 f_y A_{sv} \frac{d}{s_v}$$

VI. CONCLUSION

The main objective of the present study is to demonstrate the importance of shear hinges in seismic evaluation of RC framed building. Different methods to estimate shear strength and displacement capacity are studied. These calculation procedures are discussed through example calculations in Chapters 3 and 4. There is no published literature found on the nonlinear force-deformation model of RC rectangular section for shear. A model for nonlinear shear force versus shear deformation relation is developed using FEMA 356, IS 456:2000 . Beams and columns in the present study were modelled as frame elements with the centrelines joined at nodes using commercial software SAP2000 (v14). The rigid beamcolumn joints were modelled by using end offsets at the joints. The floor slabs were assumed to act as diaphragms, which ensure integral action of all the vertical lateral load

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resisting elements. The weight of the slab was distributed as triangular and trapezoidal load to the surrounding beams. M 20 grade of concrete and Fe 415 grade of reinforcing steel were used to design the building. The column end at foundation was considered as fixed for all the models in this study. All the building models were then analysed using non-linear static analysis. At first, the pushover analysis is done for the gravity loads (DL+0.25LL) incrementally under load control.

VII. ACKNOWLEDGEMENTS

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