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Performance Based Analysis of Composite Structure

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Abstract:
Performance-Based Plastic Design (PBPD) method has been recently developed to achieve enhanced performance of earthquake resistant structures. The design concept uses pre-selected target drift and yield mechanism as performance criteria. This study investigates the seismic behavior of concrete-filled rectangular steel tube (CFRT) structure, a push-over analysis of a 10-story moment resisting frame (MRF), for Composite (composed of CFRT columns and steel beams) structure was conducted using ETABS 2013. The M-φ curves and P-M interaction surfaces of the CFRT column (AISC 360-10) and Steel beam (AISC-LRFD-93) are calculated for push-over analyses with user defined hinges.
The Composite frame showed much improved response meeting all desired performance objectives, including the intended yield mechanisms and the target drifts. The results show that the ductility and seismic performance of Composite (CFRT) structure is superior. Consequently, Composite (CFRT) structures are recommended in seismic regions. This study shows that the PBPD approach can be successfully applied to Composite moment frame structure as well.

Keywords*: PBPD, CFRT, Target drift, Yield mechanism, M-φ curve, P-M interaction curve, User defined hinge, story drift, ductility, push-over analysis*

1. Introduction

It is noticed in the recent major earthquakes, that the seismic risk in urban areas is increasing and the infrastructure facility is far from socio-economically acceptable levels. There is an urgent need to reverse this situation and it is believed that one of the most promising ways of doing this is through the performance Based Plastic Design (PBPD) method (Lee and Goel, 2001) in which the structural design is based on the predicted performance of the structure during an earthquake The methodology used here is direct design method which uses pre-selected target drift and yield mechanisms as key performance criteria from the very start, eliminating or minimizing the need for lengthy iterations to arrive at the final design that determine the degree and distribution of expected structural damage. It is based on the formulations derived from the capacity-spectrum method using Newmark–Hall (1982) reduction factors for the inelastic demand spectrum. The design base shear for a particular danger level is calculated by equating the work needed to push the structure monotonically up to the target drift to the energy required by a corresponding Elasto-Plastic Single Degree of Freedom system to achieve the same state.

2. Composite Structure

Recent trends in the construction of moment-framed buildings show the increased use of steel, reinforced concrete, and composite steel-concrete members functioning together in what are termed *composite*, *mixed* and/or *hybrid* systems. Such systems make use of each type of member in the most efficient manner to maximize the structural and economic benefits. As shown in Figure1, one example of a composite system consists of concrete filled steel tube (CFT column) column and Steel beams. This system is also known as Concrete Filled Steel Tube (CFST) Structural System and it is the focus of this research.

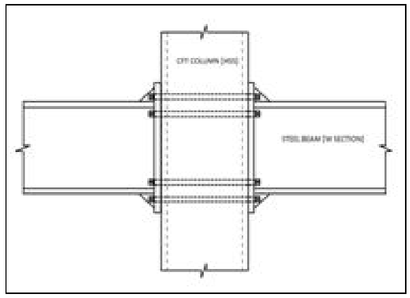

Figure 1: Schematic of typical CFT Column and Steel Beam Composite System

2.1. Evolution of Composite Construction

The first study of steel-concrete composite members began as early as 1908 at Columbia University (Viest, Colaco et al., 1997). The combined material strength was not appreciated in the early days and the design concept considered two individual materials by either conservatively neglecting the contribution from one or another or by adding them separately. An early composite beam system that gained popularity was a concrete slab on steel beam with mechanical shear connectors. Later, other composite forms including concrete filled steel tube (CFT) construction where concrete is placed in a hollow steel member, reinforced-concrete steel (RCS) construction with RC columns and steel beams, and construction with steel-reinforced concrete (SRC) columns, became popular. SRC columns involves with steel members surrounded by concrete.

Although CFST columns are suitable for tall buildings in highly seismic regions but its use has been limited due to a lack of information about the true strength and inelastic behavior. Due to the traditional separation between structural steel and reinforced concrete design, the recommended procedure for designing CFST column are found different, for example, recommendations of American Concrete Institute's (ACI) code is quite different from the Load and Resistance Factor Design (LRFD) approach suggested by the American Institute of Steel Construction (AISC).The exact behavior of concrete and steel under axial load is yet to be understood properly. The behavior of this type of composite structure is very complicated in nature even under axial load. The use of high strength CFST column in the construction industry is still limited owing to the lack of understanding of its structural behavior and insufficient recommendations in the design codes.

2.2. Merits of CFT Structure

- Premature local buckling of steel tube is delayed and strength degradation is moderate due to the restraining effect from concrete.
- Concrete can develop higher compressive strength due to confining effect from the steel tube. Concrete and steel are completely compatible and complementary to each other as they have almost same thermal expansion and they have an ideal combination of strengths with the concrete efficient in compression and the steel in tension.
- Strength degradation of concrete is not so severe due to spalling is prevented by steel tube. Creep and drying shrinkage of concrete infill is smaller than conventional exposed concrete.
- Steel element in CFT is well plastified due to the outermost location in the section and concrete improves fire resistance of the steel tube.
- Composite construction, particularly that uses CFTs, allows rapid construction as there is no need for form work construction. In addition, waiting for curing time of concrete is not necessary as construction of upper storey can proceed before curing of concrete in the lower storey.
- Construction site is cleaner and produces less waste.
- Concrete in CFTs can be easily crushed and separated from steel tube. Hence both materials can be entirely recycled.

The main disadvantage of composite construction is the need to provide corrosion and fire resistant coatings. Another minor drawback is that it is somewhat more complicated than other methods to design and construct. These drawbacks need some consideration; however, are far outweighed by the significant advantages that can be gained.

3. Pushover Analysis

The static pushover analysis is becoming a popular tool for seismic performance estimation of existing and new structures. This analysis method, also known as sequential yield analysis or simply "Pushover" analysis has gained significant popularity during past few years. It is one of the three analysis techniques recommended by FEMA 356, FEMA 440 and a main component of Capacity Spectrum Analysis method (ATC-40). The expectation from the pushover analysis is, it will provide sufficient knowledge on seismic demands applied through the design ground motion on the components and its structural system. By subjecting a structure to a monotonically increasing pattern of lateral forces a pushover analysis is performed, representing the internal forces which would be experienced by the structure when subjected to ground shaking. Under incrementally increasing loads various structural elements experiences a loss in stiffness. Using a pushover analysis, a characteristic nonlinear force-displacement relationship can be determined.

4. User Defined Hinge

The definition of user-defined hinge properties requires moment–curvature analysis of each element. For the problem defined, building deformation is assumed to take place only due to moment under the action of laterally applied earthquake loads. Thus user-defined M3 hinge was assigned at beam member ends and P-M2-M3 hinge was assigned to column member ends where flexural yielding is assumed to occur. Moment-curvature relationship was assigned in ETABS-2013 for both confined and unconfined cases to represent the flexural characteristics of plastic hinges at the ends.

4.1. Moment curvature analysis of steel beam(W300mmx50)

	Moment	**Es x Ixx**	**Curvature**
	M kNm	EI kNm^2	Phi, rad/m
M_y	362.114896	32386.45	0.011181
M_p	406.172668	32386.45	0.012541

Table 1: values of yield moment and plastic moment for steel beam

The values in the above table are the moment curvature properties of the steel beam, calculated using excel sheet, which is required to generate the user defined plastic hinges.

Points	**Moment/SF**	**Curvature/SF)**
A (origin)	0	0
B (yeilding)	1	0.009
C (ultimate)	1.107343	0.015
D (Strain hardening)	0.2	0.015
E (Strain hardening)	0.2	0.135

Table 2: ETABS-2013 Input of Moment curvature values for steel beam (SF-scale factor)

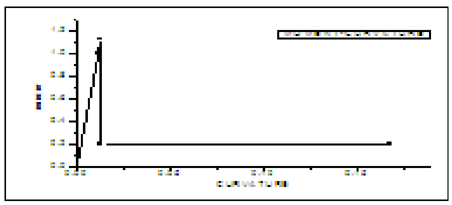

Figure 3: moment curvature curve

4.2. Interaction Curve and Moment curvature analysis of CFT column(HSS-500X300X12.5mm)

interaction points	**axial force P in kN**	**moment M in kNm**	**flexural rigidity ei in kN-m^2**	**curvature kpt or phi rad/m**
A	8701.729	0	172711.207	0
E	4973.151	839.3354	172711.207	0.00486
C	3091.961	1059.635	172711.207	0.006135
D	1545.981	1115.916	172711.207	0.006461
B	0	1059.635	172711.207	0.006135

Table 3: Interaction curve for CFT column

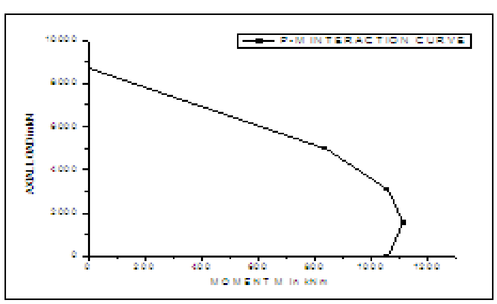

Figure 4: P-M interaction curve for CFT column

The interaction diagram of the columns was drawn to determine if the maximum axial load and moment exceeded the capacity of the column.

Points	Moment/SF	Curvature/SF)
A (origin)	0	0
B (yeilding)	1	0.004859762
C (ultimate)	1.3295	0.006461165
D (Strain hardening)	0.2	0.006461165
E (Strain hardening)	0.2	0.072896432

Table 4: ETABS-2013 Input of Moment curvature values for CFT column (SF-scale factor)

Moment curvature values converted with scale factor considering yield moment and ultimate moment and for which the corresponding curvature value is taken.

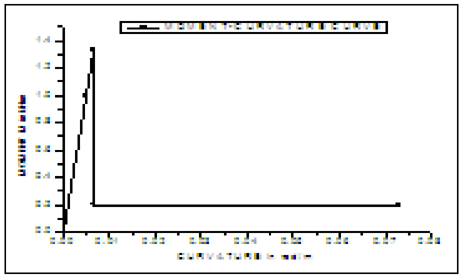

Figure 5: Moment curvature curve for CFT Column

5. PBPD Method

The main goal of performance based design i.e. a desirable and predictable structural response can be achieved by accounting in-elastic behavior of structures directly in the design process. Figure.6 shows the target and yield mechanism chosen for the frame while designing it using the performance based plastic design method. The hinges are to be formed at the bottom of the base column and in beams only. The beams are modeled to behave in-elastically, while the columns are modeled (or „forced‟) to behave elastically.

The seismic Parameters used for the study were, Yield drift ratio θy = 1%, Target drift ratio θu=4%, Inelastic drift ratio θp= θu-θy=3%, Ductility factor μs= θu/ θy=4, Reduction Factor due to Ductility Rμ= 3, Energy Modification Factor γ=0.778 (Newmark and Hall., 1982, Dr.S.B.Kharmale.,et al.,2012, and IS 1893-2002.)

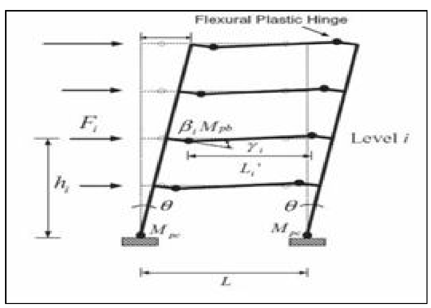

Figure 6: Target drift and Yield mechanism for moment resisting frame designed using PBPD approach. [Lee and Goel.. (2001)]

6. Design Parameters

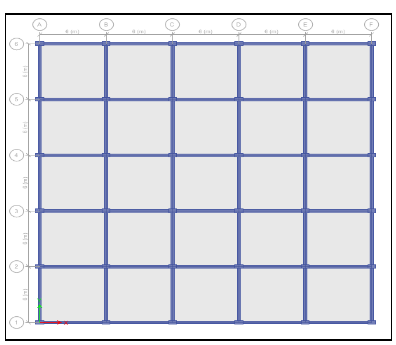

Figure 7: Typical Plan of Moment Resisting Frame

Frame type- : Composite (CFT) moment resisting frame	
Number of storey-	: 10
Number of bays in X-direction	: 5
Number of bays in Y-direction-	: 5
Spacing in X-direction-	: 6m
Spacing in Y-direction-	: 6m
Thickness of slab	: 125mm
Building Height	: 31m (4m + 27m)
Steel for beam	: ASTM-A992 GRADE 50=>Fy=344.74N/mm2
Steel for CFT column:ASTM-A500 GRADE B => Fy=317.16 N/mm2	
Concrete	: 4000 psi => fc= 27.57 N/mm2
Design loads	
Live load (LL)	: 3 kN/m2 for Floor and 1.5 kN/m2 for Roof
Floor finish and Ceiling finish (FF)	: 1.5 kN/m2
Earthquake parameter (Dr. S.B. Kharmale.,et al.,2012)	
Importance factor- I	: 3
Response reduction factor-R	: 8
Type of soil-	: class D (stiff soil)
Damping of structure-	: 5%
Codes Used	: AISC 360-10, AISC-LRFD-93,ASCE 7-10

Table 5: Design Data for Composite (CFT) Moment Resisting Fram

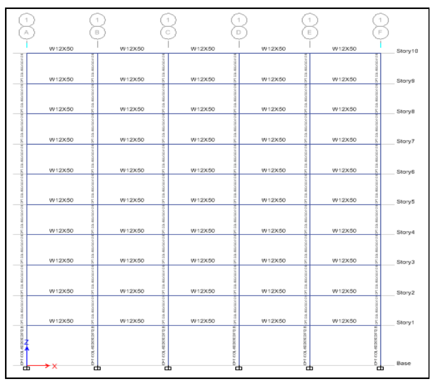

Figure 8: Elevation of Moment Resisting Frame

STOREY LEVEL	COLUMN SIZE	BEAM SIZE
1st to 5th and 6th to 10th	HSS-500mmx300mmx12.5mm (20”X12”X1/2”)	W-300mm x 50 W-12”X50
Seismic weight : 71327.85 kN		

Table 6: designed dimensions and seismic wt

7. Results

7.1. Nonlinear Static Analysis result

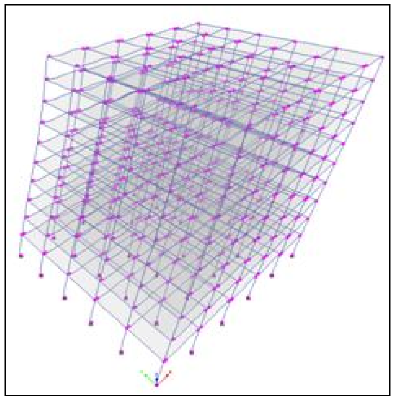

Figure 9: Formation of Plastic hinges in the Composite frame designed using PBPD approach

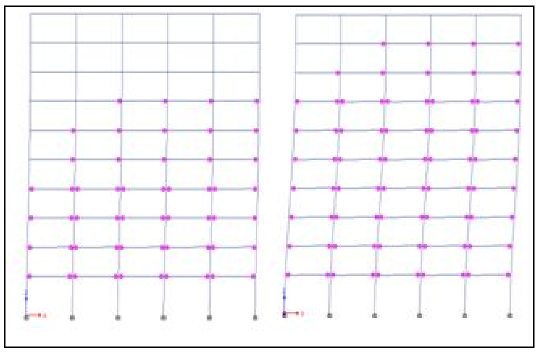

Figure 9 (a): Formation of Plastic hinges at step 2 & 3 in the frame designed using PBPD approach

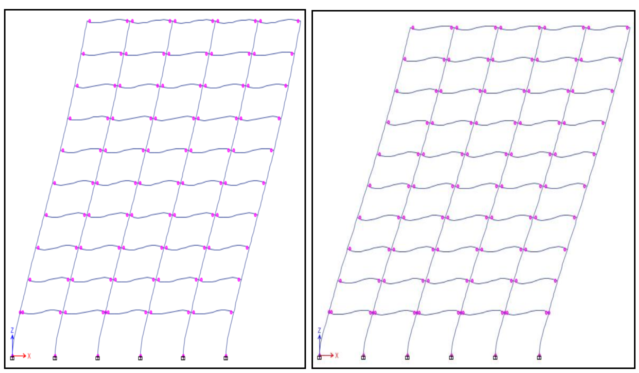

Figure 9 (c): Formation of Plastic hinges at step 12 & 13 in the frame designed using PBPD approach

In the figure 9 (a) it could be clearly seen that hinges are formed in beams only at the step 2 and in step 3. It is observed that the hinges are formed in the beam of upper storey and at the column base in the step 5. In step 8 it is clearly observed that the hinges are formed at all the beams and only at the base of the column, which converts the whole structure into a mechanism and avoids the total collapse. In the figure.9 (c), the hinges are formed in the column after formation of hinges in all beams at step 12 and in the step 13 only the column hinge formation is observed. The reason is that the PBPD method is based on the "strong column weak beam" concept and the beams fails first. As the structure turns into a mechanism due to formation of hinges in beams it undergoes large deformation before failure.

7.2. Pushover Curve

COMPOSITE MRF	
MONITERED DISPLACEMENT in mm	**BASE FORCE in kN**
1240	8788.9253
1162.4	8781.0794
1038.4	8768.5472
914.4	8756.0135
790.4	8743.4781
666.4	8730.9428
542.4	8718.4075
418.4	8705.8722
356.3	8294.5261
230.7	6165.8093
124	3314.3244
0.01278	0

Table 7: pushover curve of d Composite structure

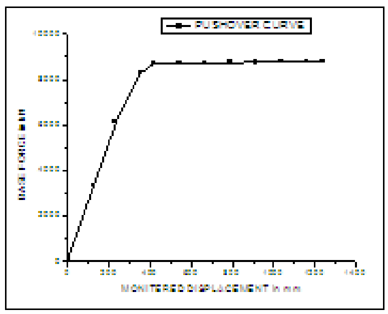

Figure 10: pushover curve of Composite structure

In the above figure.10, the Composite structure reached up to target drift 1240mm with base force8788.93 kN. Hence it is clear that the Composite frame is more ductile than the RC frame. The performance of the Composite frame is discussed below.

7.3. Performance Point

Performance point determined from pushover analysis with user defined hinges is the point at which the capacity of the structure is exactly equal to the demand made on the structure by the seismic load. The performance of the structure is assessed by the state of the structure at performance point.

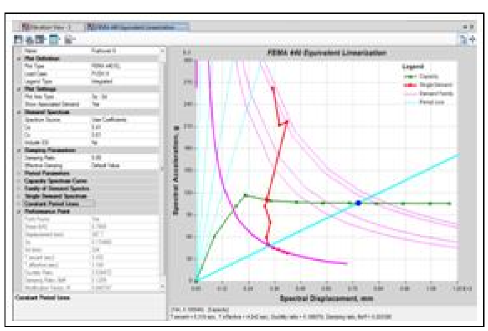

Figure 11: Performance point of Composite frame designed using PBPD method

Figure shows the performance point of Composite moment resisting frame with a displacement of 387.7 mm with values Ca = 0.41 and Cv = 0.61.(ATC 40)

Frame type (PBPD frame)	Spectral acceleration (Sa)	Spectral displacement Sd (mm)	Base Shear V(kN)	Roof Displaceme nt D(mm)
COMPOSITE MRF	0.11046	324	8747.65	387.7

Table 8: Performance point parameters

7.4. Story Drift

The storey drift is calculated for both buildings along longitudinal direction for the PBPD method. The results are listed in the Table and corresponding graphs are shown in Fig

STORY LEVEL	ELEVATION in m	COMPOSITE MRF
Story10	31	0.001276
Story9	28	0.001873
Story8	25	0.002761
Story7	22	0.004383
Story6	19	0.008815
Story5	16	0.024906
Story4	13	0.04427
Story3	10	0.054919
Story2	7	0.058565
Story1	4	0.057117
Base	0	0

Table 9: the values of story drift in X-dir. for Composite MRF

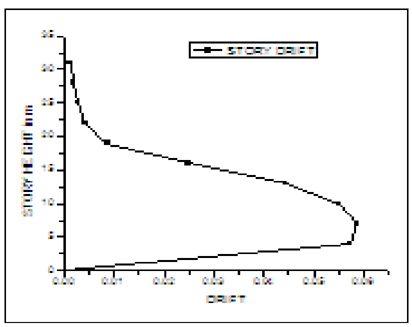

Figure 12: the story drift of Composite frame

From the fig 12 it is observed that the story drift is more in the lower story as compared to increase in the story level. Hence strengthening of column is necessary to reduce the drift effect. In the Composite frame also the drift is more at level 4m to 10m after that the drift is linear up to the top story. At the first story i.e., at 4m height both frames have more drift as compared to the top story. From the above fig it is clear that the CFT column has to be strengthened up to 10m height (i.e., up to 3rd story) to reduce the story drift.

8. Conclusion

- The Structure is designed taking into consideration its inelastic properties. This leads to the optimum utilization of the sections. The calculated moment curvature values and interaction curve values are input in the hinge property command for all the structural members of Composite moment resisting frame.
- For the model studied, Non Linear Static (Pushover) analysis shows very good behavior of the PBPD frame under static pushover loads as compared to elastic design frame.
- From the interaction curve calculation for CFT column, it is concluded that the moment capacity of CFT column is 1115.916 kNm and the axial load carrying capacity is 8701.729 kN.
- In the composite structure the hinge formation is first in the beam and then in the column after the formation of all the hinges in the beam. That means composite structure gives better result for yield mechanism. Hence the PBPD method (by Lee and Goel) is validated for composite (CFT column and Steel beam) framed structure, which meets the objective.
- From the story drift fig 12 it is concluded that structure required to be strengthened up to different story level. i.e., up to 5th story to reduce the drift effect.

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