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Seismic Evaluation of Different Structural Systems in Stepped Building Frame

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***Abstract:** High rise structures have fascinated mankind from the beginning of the civilization itself. In the last few decades the rate of growth in vertical structures has increased drastically. Seismic performance of a building is an important criteria to be considered in the design phase. Many building nowadays have irregular configuration both in plan and elevation. Usually, irregularities are unavoidable in the construction of buildings. This causes the structure to be more vulnerable to damages during earthquakes. Hence, it is necessary to assess the seismic performance of a structure in the design phase. In this work, a hybrid system which is a combination of conventional lateral load resisting system (bracings and shear wall) and a moment resisting frame is used, to improve the seismic performance of vertical irregular structures such as stepped building. Vertical discontinuity arises from reduction of the lateral dimension of the building along its height commonly known as stepped building. Different types of concentric bracing systems have been used. The regularity index provides a basis for assessing the degree of irregularities in a stepped building frame. Torsional effect of structures were also studied. The performance of the structure is assessed by means of modal analysis and nonlinear time history analysis in SAP 2000 (version 2014).Shear wall with concentric brace and shear wall with X brace turned out to be the best hybrid system in terms of seismic performance.*

***Index Terms:** Stepped building frame, Dual system, Hybrid system, Regularity index*

I. INTRODUCTION

Many buildings in the present scenario have irregular configuration in both plan and elevation. Irregularities are not avoidable in the construction of buildings. Irregularities in buildings will cause damage during earthquakes. In multistoried buildings, damage from earthquake ground motion generally initiates at locations where the structure is weak[2]. Structural weaknesses may be caused by discontinuities in stiffness, strength and mass difference between adjacent storeys.Real structures are mostly irregular, as perfect regularity is an idealization that occurs rarely. For practical purposes, major seismic codes distinguishes irregularity in plan and elevation.One of the greatest causes of damage to buildings has been the use of improper architectural- structural configurations which affects building response.A common form of vertical discontinuity arises from the reduction of the lateral dimension of the building along its height, Such buildings are commonly known as stepped buildings. Stepped buildings with vertical discontinuity have increased recently because of its functional and aesthetic architecture. Stepped form provides adequate daylight and ventilation in an urban locality with closely spaced tall buildings [5]. Stepped buildings are characterized by staggered abrupt reductions in floor area along the height of the building.

II. STEPPED BUILDING FRAME

Stepped buildings are characterized by abrupt reductions in floor area along the height of the building. Height-wise changes in stiffness and mass, imparts render the dynamic characteristics to a stepped building. Stepped buildings are a typical form of vertical geometric irregularity that required special design consideration due to transverse and torsional responses and higher mode effects. As per IS 1893:2016, stepped building forms are to be treated as vertically irregular when the lateral dimension of the maximum offset (A) at the roof level exceeds 25% of the lateral dimension of the building at the base (L) as shown in Fig.1.

Fig. 1 Stepped building frame

A. Structural systems

A structural system consists of elements which are used to resist the various combinations of vertical and horizontal loads. The selection of one structural system depends on various factors such as location, height and architectural requirements of the building [6]. One of the major consideration in the modern office building is the requirement of large working spaces. Therefore all the load carrying members especially the lateral load resisting members are placed over the exterior periphery and at the core of the structures. Currently there are different forms of structural systems, out of which moment resisting frame, braced frame and shear wall framed system are the conventional types.

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Building frame with shear wall and structural system (bracing) combination is called hybrid system. In this study various structural systems are to be used such as;

- Rigid Frame System
- Braced Frame system
- Shear wall frame system

III. METHODOLOGY

A. Problem formulation

A stepped building frame subjected to gravity loading was first modelled and designed and then design check is carried out as per IS 456: 2000. The structure was successful in the final design check carried out under gravity loads. Then seismic analysis (Modal analysis and nonlinear time history analysis) as per Indian seismic code has been carried out. After the seismic analysis, the seismic design check has been carried out. That is the structure can take gravity load but has poor performance under seismic loads. So, this structure requires an efficient lateral load system to resist the additional loads generated due to the seismic ground motion. The reason for poor performance was investigated and it was found that mass irregularity, discontinuity in strength and stiffness. This is how stepped building structures shows poor performance during seismic ground motions, in the absence of an efficient lateral load resisting system. The dual frame system specified by Indian seismic code and a new structural system known as the hybrid structural systems are chosen to improve the seismic performance of this structure. The data chosen for the modeling of building frame as shown in Table I.

Table I Preliminary data [5]

Building type	Office
Zone factor, z	0.16
Zone	II
Importance factor,I	1
Response reduction factor,R	5
Damping (% critical)	5
Soil type	Medium
Plan dimension (m)	24 x 24
Bay width in x and y direction(m)	6
Upper storey height (m)	3.3
Opening area in infill (m)	1.5 x 1
Opening area in shear wall (m)	1 x 2
Ground storey height (m)	4.5

B. Validation

A regular bare frame has been modelled and analysed using response spectrum analysis. The base shear obtained after the analysis using SAP 2000 (version 2014) has been compared with the base shear obtained by theoretical calculation.

C. Modelling of building frame

The modelling of the structures had been carried out in SAP 2000(version 2014). The beams and columns are modelled as frame elements. The slab and shear wall are modelled as thin shell element. The external infill wall is modelled as diagonal strut element. The material data chosen for study is shown in Table II. The model parameters are shown in Table

Table II Material property

Material	Type	Young's modulus, E (N/mm^2)	Density,ρ (kN/m^2)
Concrete	M25	25000	25.00
Rebar	Fe 415	200000	78.93
Brick	Class 490	5500	18.87

Table III Modal parameter [28]

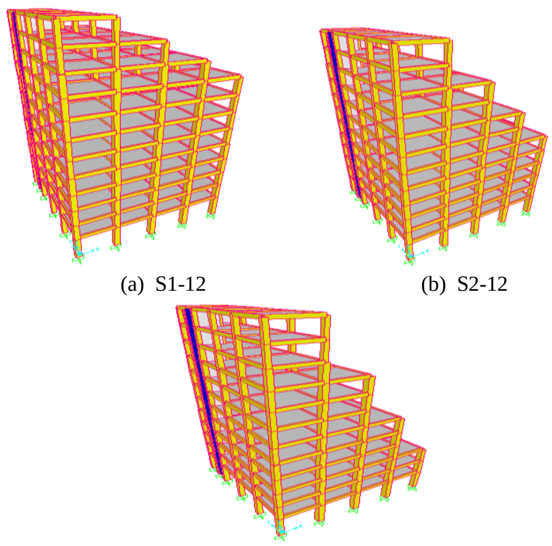
Parameter	Dimensions
Slab thickness	150mm
Wall thickness	230mm
Shear wall thickness	250mm
Structural steel section	ISMB 300

D. Computational model

Modelling a building involves the modelling and assemblage of its various load-carrying elements. The model must ideally represent the mass distribution, strength, stiffness and deformability. Modelling of the material properties and structural elements used in the present study is described in Table II. Building frame and notations are shown in Table IV. Different structural models chosen are shown in Fig. 2.

Table IV Building frame and notations

Building frame	Notations
12 storey Stepped builing with one floor height	S1 – 12
12 storey Stepped builing with two floor height	S2 – 12
12 storey Stepped builing with three floor height	S3 - 12
Bare frame	BF
X brace	XB
Diagonal brace	DB
Chevron brace	CB
Shear wall	SW
Shear wall with X brace	SW-XB
Shear wall with diagonal brace	SW-DB
Shear wall with inverted brace	SW-CB



(a) S1-12 (b) S2-12

(c) S3-12

Fig. 2 Structural models

IV. RESULTS AND DISCUSSIONS

A. Modal analysis

Modal analysis as per Indian seismic code were carried out on dual frame models such as XB, SW, CB, DB and on hybrid frame models such as SWXB, SWCB and SWDB. 79 models were considered for the analysis.

a. Variation in fundamental natural period

The variation in fundamental time period of set back structure with structural systems are shown in Table V.

Table V Variation in fundamental natural period of 12 storeyed stepped building frame

Models	Fundamental time period (s)		
	S1	**S2**	**S3**
BF	1.47	1.22	1.18
XB	**0.96**	**0.84**	**0.80**
CB	1.00	0.95	0.91
DB	1.27	1.12	1.06
SW	**0.66**	**0.63**	**0.59**
XBDB	1.14	1.04	0.99
XBCB	1.00	**0.95**	**0.89**
DBCB	1.20	1.14	1.06
SWDB	**0.78**	**0.71**	**0.65**
SWCB	**0.59**	**0.52**	**0.49**
SWXB	**0.48**	**0.42**	**0.40**

From the result obtained for the fundamental period, it is observed that the time period of the systems increase with increasing number of storeys. By using dual frame in stepped building frame fundamental natural period of structure decreased due to increase the stiffness of structure and SW dual frame system is found to be more effective in the combinations considered. And also by using hybrid frame in stepped building frame natural period of structure decreased due to increase the stiffness of structure. It can conclude that dual and hybrid systems are more effective in high rise stepped building frame.

b. Quantifying irregularity in stepped building frame

The stiffness and mass distributions in the frame have to be considered in quantifying the irregularity of a stepped building. Studying the dynamic properties of regular building it was found that the participation of the first mode is dominant. However, when the vertical irregularities (step in the building frame) are introduced, it is observed that as the irregularity increases, participation on higher modes is prominent. Generally, irregularity in the stepped frame can be captured by relative first mode participation factor. Accordingly, a regularity index (η) is proposed to quantifying irregularity of a stepped frame as Eqn.5.1. [5]

$$\eta = \frac{\Gamma_1}{\Gamma_{ref}} \quad (5.1)$$

Where,

Γ_1 is the first mode participation factor for stepped frame under consideration

Γ_{ref} is the first mode participation factor for regular frame without steps

Building irregularity of 12 storeyed stepped building frame is shown in Table VI to Table VIII. From Table VI to Table VIII, it can be concluded that for any stepped building the value of regularity index (η) will be less than unity as the first mode participation factor will always be less than that of regular building. This regularity index accounts for properties associated with mass and stiffness distribution in the frame. Regularity index increases with increasing in number of storeys, the rate of increasing regularity index being stiffer when the number of storeys per step increases.

Table VI Building irregularity of 12 storeyed stepped frame with S1

Building frame		Regularity index	Percentage Variation
S1	S1BF	0.59	-
	XB	0.77	30.51
	CB	0.76	28.81
	DB	0.74	25.14
	SW	**0.95**	**61.02**
	XBDB	0.76	28.81
	XBCB	0.79	33.90
	DBCB	0.72	22.03
	SWDB	0.87	47.46
	SWCB	0.90	52.54
	SWXB	**0.92**	**55.93**

Table VII Building irregularity of 12 storeyed stepped frame with S2

Building frame		Regularity index	Percentage Variation
S2	S2BF	0.51	-
	XB	0.74	45.10
	CB	0.72	41.18
	DB	0.70	37.25
	SW	**0.92**	**80.39**
	XBDB	0.72	41.18
	XBCB	0.75	47.06
	DBCB	0.68	33.33
	SWDB	0.84	64.71
	SWCB	0.88	72.55
	SWXB	**0.90**	**76.47**

Table VIII Building irregularity of 12 storeyed stepped frame with S3

Building frame		Regularity index	Percentage Variation
S3	S1BF	0.48	-
	XB	0.73	54.15
	CB	0.70	45.83
	DB	0.67	39.58
	SW	0.83	72.92
	XBDB	0.70	45.83
	XBCB	0.72	50.00
	DBCB	0.65	35.42
	SWDB	0.79	64.58
	SWCB	**0.84**	**75.00**
	SWXB	**0.87**	**81.25**

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B. Non linear time history analysis

Time history analysis (Elcentro – earthquake data) is a step by step analysis of the dynamic response of a structure subjected to a specific ground motion. The dynamic input has been gives as a ground acceleration time – history which was applied uniformly at all the points of the base of the structure, only one horizontal component ground motion has been considered.

a. <u>Variation of roof displacement</u>

The variation of roof displacement of different building models are shown in Table IX to XI. It can be concluded that the stepped building frame without structural system have higher displacement as compared to the dual and hybrid structural systems. Roof displacement of structure increase with increasing irregularity and number of storeys.
Stepped buildings with dual frame such as SW and hybrid structural system SWXB are more effective in reduction of roof displacement of structure. While with increasing number of storeys of structure, dual frame such as SW and hybrid structural systems SWXB and SWCB are more effective in reduction of roof displacement of structure. It can be concluded that hybrid structural systems are more effective in high rise structures.

Table IX Roof displacement of 12 storeyed stepped frame with S1

Building frame		Roof displacement (mm)	Percentage Variation
S1	S1BF	30.89	-
	XB	10.11	67.27
	CB	23.86	22.76
	DB	26.49	14.24
	SW	**6.79**	**78.02**
	XBDB	17.56	43.15
	XBCB	15.03	51.34
	DBCB	21.95	28.94
	SWDB	10.54	65.88
	SWCB	9.13	70.44
	SWXB	**8.28**	**73.20**

Table X Roof displacement of 12 storeyed stepped frame with S2

Building frame		Roof displacement (mm)	Percentage Variation
S2	S2BF	35.60	-
	XB	16.74	61.06
	CB	27.57	26.00
	DB	31.24	14.11
	SW	14.56	68.11
	XBDB	22.07	43.80
	XBCB	18.78	54.45
	DBCB	27.12	27.45
	SWDB	14.32	68.89
	SWCB	**11.02**	**79.57**
	SWXB	**8.41**	**88.02**

Table XI Building irregularity of 12 storeyed stepped frame with S3

Building frame		Roof displacement (mm)	Percentage Variation
S3	S1BF	38.00	-
	XB	19.47	59.99
	CB	30.01	25.87
	DB	34.65	10.84
	SW	16.45	69.76
	XBDB	28.14	31.92
	XBCB	23.42	47.20
	DBCB	31.90	19.75
	SWDB	17.49	66.40
	SWCB	**15.91**	71.51
	SWXB	**11.43**	**86.01**

B. Variation of base shear

The variation of base shear of different building models are shown in Table XII to Table XIV. It can be seen that stepped building frame without structural system have lesser base shear as compared to the dual and hybrid structural systems. Base shear of structure decrease with increasing irregularity and increase with increasing number of storeys.
Stepped buildings with dual frame such as SW and hybrid structural system SWXB are more effective in improving base shear of structure. While with increasing irregularity of structure hybrid systems SWXB and SWCB are more effective. When number of storeys of structure is increased, dual frame such as SW and hybrid structural systems SWXB and SWCB are more effective in improving base shear of structure.

Table XII Base shear of 12 storeyed stepped frame with S1

Building frame		Base Shear (kN)	Percentage Variation
S1	S1BF	620	-
	XB	654	5.48
	CB	648	4.52
	DB	640	3.23
	SW	**820**	**32.26**
	XBDB	640	3.23
	XBCB	653	5.32
	DBCB	646	4.19
	SWDB	720	16.13
	SWCB	795	28.23
	SWXB	**864**	**39.35**

Table XIII Base shear of 12 storeyed stepped frame with S2

Building frame		Base Shear (kN)	Percentage Variation
S2	S2BF	560	-
	XB	598	6.79
	CB	581	3.75
	DB	579	3.39
	SW	**710**	**26.79**

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	XBDB	576	2.86
	XBCB	592	5.71
	DBCB	588	5.00
	SWDB	592	5.71
	SWCB	694	23.93
	SWXB	**758**	**35.36**

Table XIV Base shear of 12 storeyed stepped frame with S3

Building frame		**Base Shear (kN)**	**Percentage Variation**
S3	S3BF	495	-
	XB	535	8.08
	CB	526	6.26
	DB	519	4.85
	SW	622	25.66
	XBDB	519	4.85
	XBCB	534	7.88
	DBCB	528	6.67
	SWDB	586	18.38
	SWCB	**642**	**29.70**
	SWXB	**663**	**33.94**

V. CONCLUSIONS

The seismic performance of stepped building with hybrid structural system and dual frame system was investigated. Modal analysis and non - linear time history analysis were used to study the seismic performance of the structural systems. The poor performance of stepped building can be accounted due to mass reduction at top storeys which reduces the storey stiffness. This causes an increase in lateral displacement and twisting effect in stepped building frame during seismic ground motions, which leads to catastrophic failures.

- Structural systems are found to be more effective with increasing number of storeys.
- The given configuration of shear wall dual frames system improves the seismic performance of stepped building by reducing lateral displacement and base shear.
- The implementation of hybrid structural systems has reduced the irregularity effect and increased the mass and stiffness of the system.
- The best hybrid framed systems that can be adopted in stepped buildings are SWCB and SWXB. These systems have high lateral and vertical load carrying capacity.
- While considering the practical aspects, it is better to provide SW-CB system, since it creates much convenience for the movement of peoples and vehicles in ground storey.

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