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Behaviour of Outrigger Beams in High rise Buildings under Earthquake Loads

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Abstract

Tall building development has been rapidly increasing world wide introducing new challenges that need to be met through engineering judgment. In modern tall buildings, lateral loads induced by wind or earthquake are often resisted by a system of coupled shear walls. But when the building increases in height, the stiffness of the structure becomes more important and introduction of outrigger beams between the shear walls and external columns is often used to provide sufficient lateral stiffness to the structure.

In general, earthquake ground motion can occur anywhere in the world and the risk associated with tall buildings, especially under severe earthquakes, should be given particular attention, since tall buildings often accommodate thousands of occupants. It is conceivable that structural collapse of such buildings can lead to disasters of unacceptable proportions.

When adopting outrigger beams in building design, their location should be in an optimum position for an economical design. A range of different strategies has been employed to identify the optimum locations of these outrigger beams under wind load. However, there is an absence of scientific research or case studies dealing with optimum outrigger location under earthquake loads.

This study aims to identify the optimum outrigger location in tall buildings under earthquake loads. A 50 storey building was investigated and three different peak ground acceleration to peak ground velocity ratios in each category of earthquake records were incorporated in this research study to provide a consistent level of approach. Response spectrum analysis was conducted and the behaviour of the building was determined considering response parameters such as lateral displacement and inter storey drift. It has been shown from this study that the structure is optimised when the outrigger is placed between 22-24 levels. Therefore it can be concluded that the optimum location of the structure is between 0.44-0.48 times its height (taken from the bottom of the building).

Keywords: Response spectral analysis, outrigger beam, lateral loading systems

1. INTRODUCTION

The lateral bracing system consisting of coupled shear walls with outriggers is one of the most efficient systems used for high rise construction to resist lateral forces caused by wind and earthquakes.

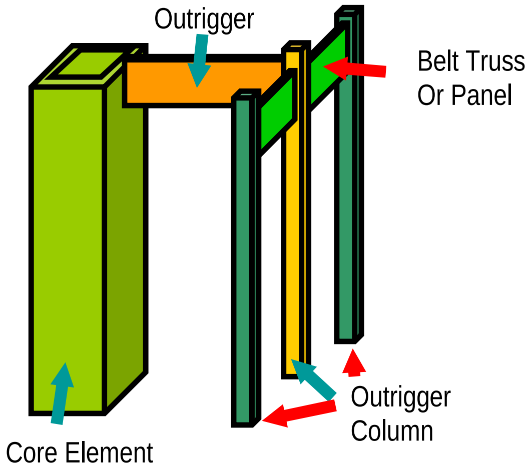


Fig 1 Shear walls with outrigger

Outrigger beams connected to the shear wall and external columns are relatively more complicated and it is understood that the performance of such coupled wall systems depends primarily on adequate stiffness and strength of the outrigger beams. Therefore overall rigidity is imperative in tall buildings in order to control lateral deflection and inter-storey drift.

Chan and Kuang (1989a,1989b) conducted studies on the effect of an intermediate stiffening beam at an arbitrary level along the height of the walls and indicated that the structural behaviour of the structure could be significantly affected by the particular positioning of this stiffening beam. Afterwards, researchers investigated novel approaches to identify the beneficial effect of an outrigger and multi outriggers on the structural behaviour and their best location along the height of the structure.

The development of simplified analytical methods for outrigger braced structures started in the mid seventies. Taranath (1974) examined the optimum location of a belt truss which minimised the wind sway and discussed a simple method of analysis. McNabb et al (1975) extended their analysis to two outriggers and investigated governing factors in drift reduction. McNabb et al (1975) verified the Taranath's (1974) optimum outrigger location result (0.445 times the height of the structure from the top of the building for a single outrigger structure) and showed that the optimum locations for two outriggers to be 0.312 and 0.685 of the total height from the top of the building. However for preliminary analysis of outrigger braced structures, simple approximate guidelines for the location of the outriggers were given in Smith at al (1991).

In most of the above investigations, the flexural rigidity of the core and axial rigidity of the perimeter columns were assumed to be uniform throughout the height of the building and the lateral loading to be uniform. But in practice, these properties would change hence Rutenberg et al (1987) investigated the effect of these properties on the behaviour of the outrigger braced structure. In 1985 Moudarres et al (1985) investigated the free vibration of high rise structures using dynamic analysis and this treatment took into account the effects of shear deformation and rotatory inertia of the core and included the inertia of the outrigger. Hoenderkamp et al (2008) presented a simple method of analysis for preliminary design of outrigger braced high-rise shear walls subjected to horizontal loading. Further Su et al (2005) investigated the complete load transfer mechanism between the outrigger brace and the core wall using strut-and-tie method. These studies showed that the position of the outrigger can substantially affect the behavior and lateral deflection of the structure.

2. STRUCTURAL MODEL

The model considered for this study is a 50 storey high rise reinforced concrete building frame and the general proto type geometry is shown in Fig 1. The height of each storey is 3.75m and all wall piers are identical with a uniform wall thickness of 450mm over the entire height. The coupling beams are all 450mm wide and uniform Grade 50 (Compressive strength 50MPa) concrete throughout the height of the building was selected for the study.

The details of the structure are given in Fig. 2 below.

No of stories	: 50 stories
Roof height	: 187.5m
Grade of concrete	: Grade 50
(For the full height of the building)	
Storey Height	: 3.75m

Member sizes

Outer Columns	: 2000x1200mm
Coupling Beam	: 450x 1000mm
Shear wall thickness	: 450mm
Outrigger Beam	: 250x3750mm

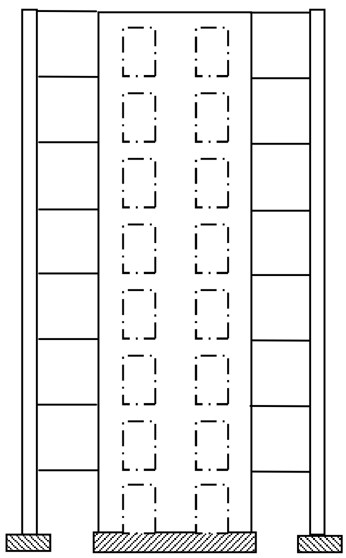


Fig 2 Elevation

The method of analysis of the above mentioned system is based on the following assumptions.

- The outriggers are rigidly attached to the core
- The core is rigidly attached to the foundation
- The sectional properties of the core, beams and columns are uniform through out the height.
- Tensional effects are not considered
- Material behaviour is in linear elastic range.

For earthquake resistant designs, a structure should meet performance requirements at two different levels, depending upon the earthquake action. The first level requires structural response in the elastic range without significant structural damage under a moderate earthquake action and the second level of performance requires that the structure doesn't collapse under a severe earthquake event with rare occurrence.

The STRAND 7 finite element package was used to simulate the model and two dimensional analysis was conducted to identify the behaviour of the structure under earthquake loads. In order to validate the model, another model was developed using the SpaceGass frame analysis package. Plate elements were used in the STRAND 7 model and beam elements were used in SpaceGass to simulate all the elements. A uniform load was applied along the height of the building in each model and static analysis was conducted to compare the results. The results obtained for maximum lateral displacement, natural frequency and vertical reaction of the outer column were compared in order to validate the model. The results obtained from both computer programs were in good agreement and the STRAND 7 model was adopted for further development to identify the global behaviour of the structure under earthquake loads.

Following validation and further development, the STRAND 7 model was used to evaluate the global behaviour of the structure using response spectrum analysis. As such, the response parameters of interest were: lateral displacement and drift index which are imperative for tall buildings with the view to limiting damage and cracking to non structural members such as facade, internal partitions and ceilings. In the process of the investigation, two options were considered depending on the number of outrigger beams in the building.

Option 1: One outrigger beam for the system
Option 2: Two outrigger beams for the system having one outrigger fixed at the top floor level.

The outriggers were assumed to be located between two floor levels and the gross section properties were used in the study.

The structure with a single outrigger was analysed as the first option and in the second option, one outrigger was placed at roof level as a fixed position and the optimum location for the other outrigger was investigated under earthquake action. Though it would structurally be inefficient to locate an outrigger at the top level, this condition can often result "naturally" for other reasons such as when a plant floor is located at the top of the building. Consequently, having considered the practical applications of outriggers, this option was chosen as Option 2 in the study.

Table 1 The fundamental periods of the building for the two options

	Mode 1	Mode 2	Mode 3	Mode 4
Option 1	0.250	0.790	1.753	2.544
Option 2	0.250	0.806	1.822	2.593

3. SELECTION OF EARTHQUAKE RECORDS FOR ANALYSIS

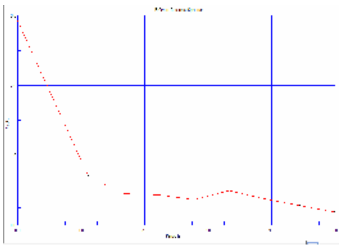
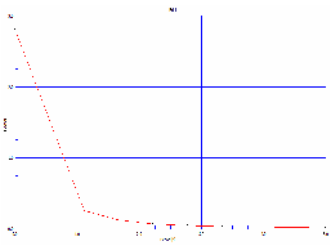
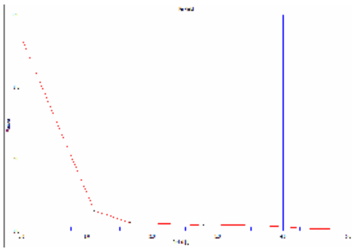
It has been observed that characteristics of recorded motions vary greatly from record to record. The intensity, duration of strong shaking and the frequency of the records depend on a number of factors such as magnitude of the earthquake, epicentral distance and local site conditions etc.

The differences in the characteristics of the recorded ground motions can lead to substantial differences in the structural response. According to Chandler's 1991 classification, the accelerograms with a short period range (<0.5s) are divided into three sets based on their A/V ratios. The records with A/V < 0.8 g/(m/s) are classified into the low A/V range, whereas those with A/V > 1.2 g/(m/s) are classified as having high A/V ratios. Records with A/V between 0.8 and 1.2 g/(m/s) are classified to be in the intermediate A/V range.

Therefore, to provide a consistent level of approach, the above mentioned classification was used in this research study and three different A/V ratios in each category were incorporated. The A/V ratios for the nine different earthquakes adopted in this study are given in Table 1 and the acceleration response spectrums for some of these earthquakes are presented in Figure 3.

Table 1 A/V ratios of selected earthquakes   Source: (Naumoski)

Record	**A/V ratios**
High A/V ratio category	
Parkfield (28 June 1966)	1.82
Friuli (6 may 1976)	2.51
Patras (29 Jan 1974)	4.72
Intermediate A/V ratio category	
Gazli (17 may 1976)	0.88
El Centro (18 May 1940)	0.96
Spitak (7 Dec 1988)	1.14
Low A/V ratio category	
Mexico City (19 Sep 1985)	0.36
Tabas (13 Sep 1978)	0.53
San Fernando (9 Feb 1971)	0.67

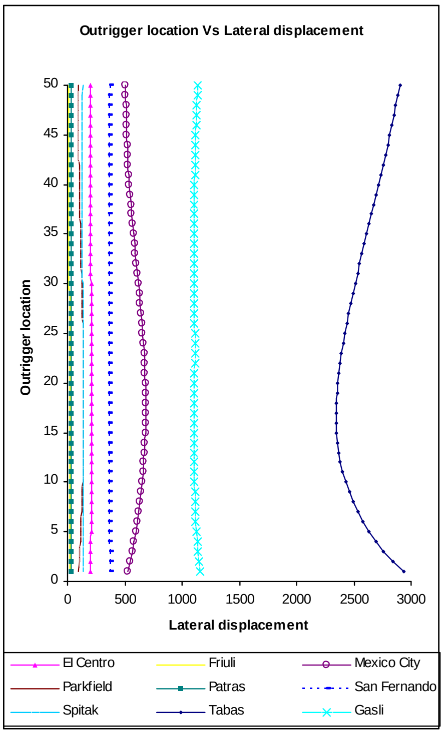
Parkfield earthquake   Friuli earthquake   Parkfied earthquake

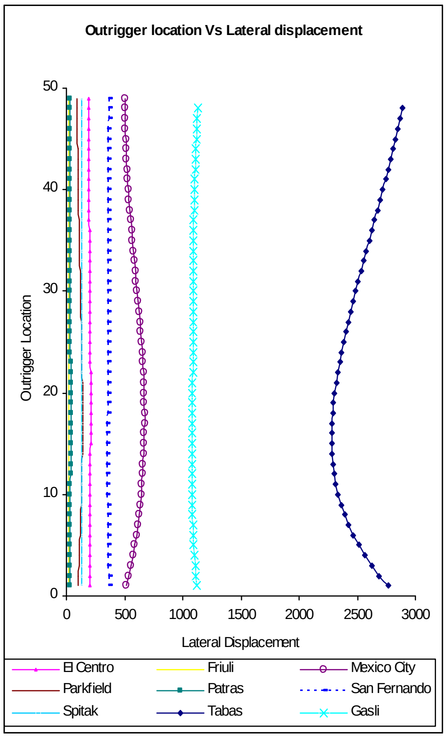
Fig 3 Acceleration response spectrums

4. RESULTS AND DISCUSSION

4.1 Maximum lateral displacement

For the model with only one outrigger (option 1), the location of the outrigger beam was changed from the first floor to the top floor in the building model and response spectrum analysis was carried out for each location for all nine earthquakes. A similar approach was adopted for the other model (option 2), with one outrigger located at the top level as the fixed location and the other outrigger beam location varied. Profiles for maximum lateral displacement for each outrigger location for these nine earthquakes were plotted for each case and their relationships were investigated. The combined graphs plotted for these results are presented in Figure 4.





(a) (b)

Fig 4 (a) Lateral displacement of the building having one outrigger
b) Lateral displacement of the building having two outriggers (one fixed at top level)

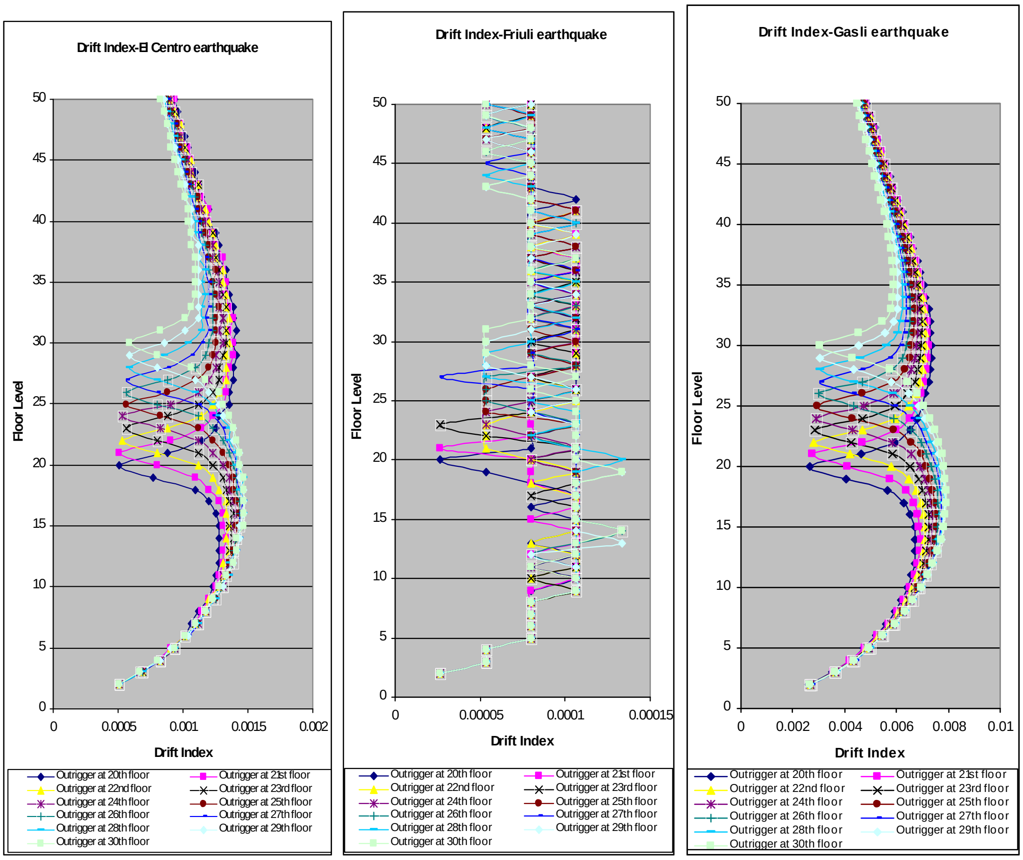
4.2 Drift index and optimum outrigger location

The drift index along the height of the building was evaluated for all nine earthquakes for several outrigger locations. In order to find out the optimum location of outrigger, analyses were carried out for both options and the graphs were plotted for each earthquake load by changing the location of outrigger from level to level. It was observed that there is a change of pattern in the profile of the graphs, when the outrigger is located between level 20 to level 30.The variation of drift index along the height of the structure obtained for option 1 is given in Figure 5.

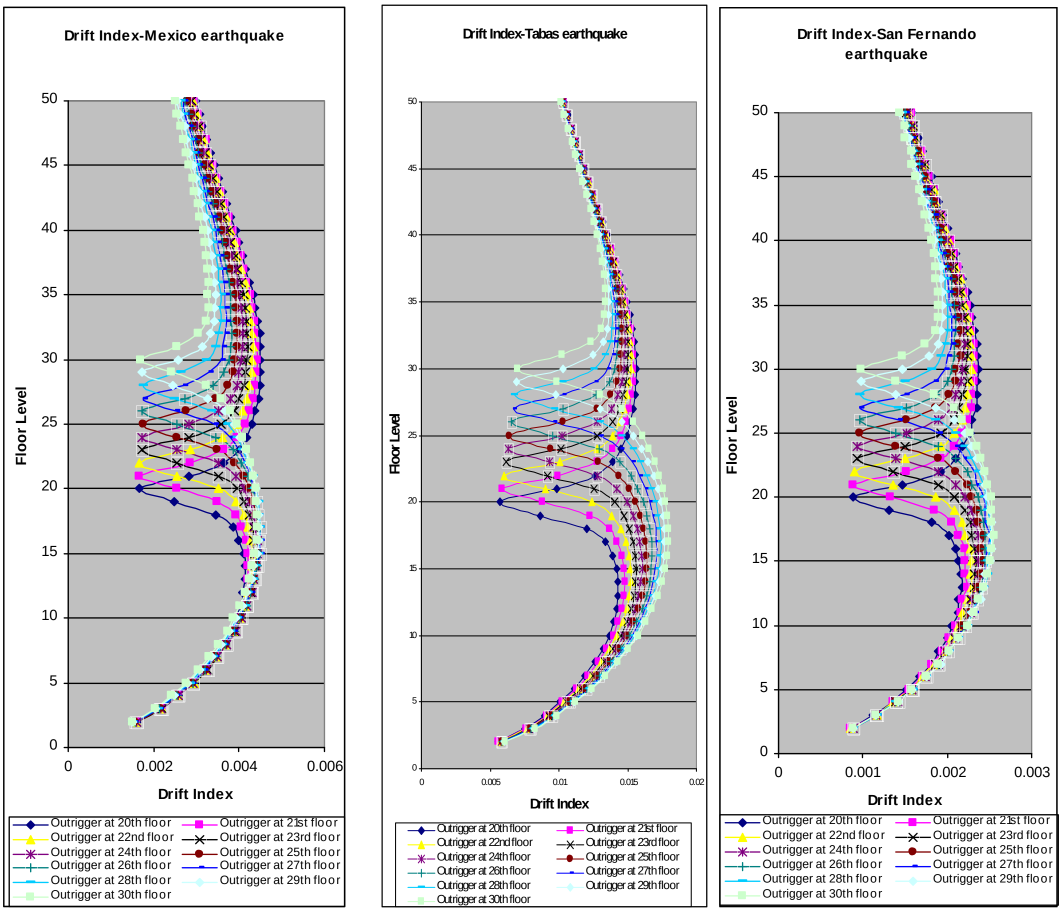
A similar analysis was carried out for option 2 for the structure with two outriggers (one always fixed at top level).

It was evident from the results for both of these options, that the drift index was low near the outrigger location. When the location of the outrigger is changed from level to level, it can be clearly seen from the graphs that, when the outrigger is located between level 20 and level 22, the maximum drift index at the levels above the location of the outrigger is higher compared to the value at the levels below the outrigger location. But when the outrigger is placed at level 24 and above, the maximum drift index at levels above the outrigger location becomes less than the values at the levels below the outrigger location. Further it can be seen that when the outrigger is placed between level 22-24, the maximum drift index below and above the outrigger location is almost the same. Therefore it can be concluded that the structure is optimised when the outrigger is placed between 22-24 levels.

Even though the structure has gone through inelastic behaviour under Tabas earthquake, there is no impact on the optimum outrigger location. However the optimum location of structures which are undergoing inelastic behaviour is beyond the scope of this study and will be continued as future work.



(a) (b) (c)



(d) (e) (f)

Fig 5 Variation of drift index for option 1 for six earthquakes
(a) El Centro earthquake (b) Friuli earthquake (c) Gasli earthquake (d) Mexico earthquake (e) Tabas earthquake (f) San Fernando earthquake

5. CONCLUSIONS

This study assessed the global behaviour of outrigger braced building under earthquake loads from which the following conclusions can be drawn based on the above results:

- The behaviour of a structure under earthquake load is different from earthquake to earthquake. This well known phenomenon is well presented in the lateral displacement results obtained for both of the options.
- The location of the outrigger beam has a critical influence on the lateral behaviour of the structure under earthquake load and the optimum outrigger locations of the building have to be carefully selected in the building design.
- The optimum outrigger location of a high rise building under the action of earthquake load is between 0.44-0.48 times the height of the building (from the bottom of the building), which is consistent with the optimal location associated with wind loading.

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