OPTIMIZED USE OF MULTI-OUTRIGGERS SYSTEM TO STIFFEN TALL BUILDINGS

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ABSTRACT :

Nowadays, in modern tall buildings, lateral loads induced by wind or earthquake forces are often resisted by a system of multi-outriggers. An outrigger is a stiff beam that connects the shear walls to exterior columns. When the structure is subjected to lateral forces, the outrigger and the columns resist the rotation of the core and thus significantly reduce the lateral deflection and base moment, which would have arisen in a free core. During the last three decades, numerous studies have been carried out on the analysis and behavior of outrigger structures. But this question is remained that how many outriggers system is needed in tall buildings.

This paper presents the results of an investigation on drift reduction in uniform belted structures with rigid outriggers, through the analysis of a sample structure were built in Tehran's Vanak Park. Results show that using optimized multi-outriggers system can effectively reduce the seismic response of the building. In addition, the results show that a multi-outriggers system can decrease elements and foundation dimensions.

KEYWORDS: Optimization, Outriggers System, Tall Buildings, Static analysis

1. Introduction

The braced frame becomes inefficient above about 40 stories because excessive bracing is required beyond that point to provide adequate lateral stiffness to the structure. The efficiency of the building structure may be improved by about 30% through the use of horizontal belt trusses that tie the frame to the core (Schueller 1977). The trusses are fixed rigidly to the core and simply connected to the exterior columns. When the shear core tries to bend, the belt trusses act as lever arms that directly transfer axial stresses into the perimeter columns. The columns, in turn, act as struts to resist the lateral deflection of the core. That is, the core fully develops the horizontal shear and the belt trusses transfer the vertical shear from the core to the outrigger frame. Thus, the building is made to act as a unit that is very similar to a cantilever tube.

The building can have one or several belt truss; the more trusses used, the better the integration of core and outrigger columns. They should be placed at locations within the building where the diagonal bracing will not interfere with the building's function. The structural principle of employing belt trusses at the top and mid-height of a building seems to be economical in applications up to approximately 60 stories (Schueller 1977). The stress diagram in Figure 1 illustrates the relative efficiency of hinging the belt trusses to the perimeter columns rather than fixing them rigidly. If the trusses were to be continuously connected to the columns, the entire system would act as a unit, thus utilizing only a small percentage of the moment-resisting capacity of the core, whose walls are relatively close to the neutral axis of the building.

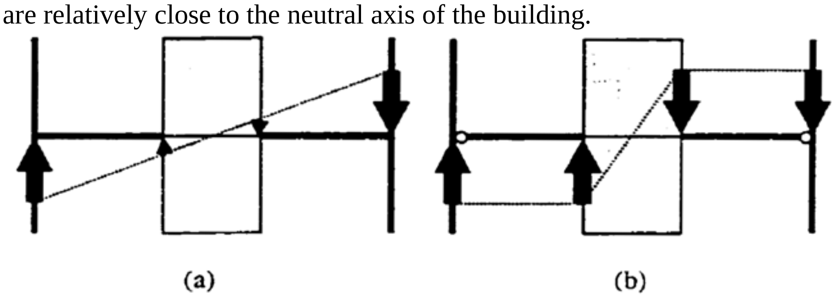

Figure 1. Stress Distribution in Frame-Shear Wall Systems with Belt Trusses

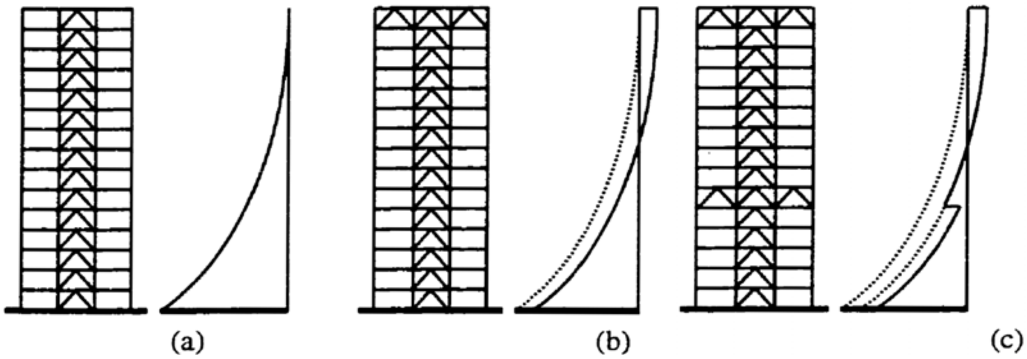

Figure 2. The Effect of Outriggers on Core Moment

This is indicated by the continuous distribution of stresses shown for the rigid frame in Figure 1.a. On the other hand, belted musses that are cantilevered from the core and hinged to the perimeter columns better develop the moment resisting capacity of the core while still engaging the exterior columns as in the rigid system (Figure 1.b). In fact, since the hinged shear connections induce no bending moments into the columns, the axial capacity of the columns is increased relative to that for the case of fixed shear connections. The response of a core frame building with belt trusses to lateral loading is shown in Figure 2. This Figure schematically shows the reduction of moment in the shear-core for a one-outrigger system (Figure 2.b) and a two-outrigger system (Figure 2. c) compared to that for a no-outrigger system (Figure 2. a).

When the frame is hinged to the core of the structure, the core behaves like a cantilever and its top is free to rotate. The frame itself hardly resists any rotation. If the frame is tied to the core by a belt truss, however, any rotation at the top of the system is restricted, since the perimeter columns tie the belt truss down. There is then no bending moment in the columns. The partial fixity provided at the top of the system by the belt truss is reflected in the moment diagram in Figure 2.b. The system no longer acts as a pure cantilever because it is restrained at the top as well as at the bottom. The resulting deflection is a flat S-curve, with a zero moment at a point of inflection above the midpoint of the building. The bending moment in the shear wall at the base of the building is less than that for the no-outrigger case in Figure 2.a. The strength and stiffness of the system is further increased by adding additional belt trusses at intermediate levels within the building. At each truss level the system is restrained from rotating. The fixity provided at these levels pulls the moment diagram back, as shown in Figures 2.c. Each that the bending moment at the base of the building is further reduced (along with building sway).

Smith and Coull (1991) studied the optimum location of outriggers by considering hypothetical structures whose outriggers were flexural rigid. They found that a single outrigger in a one-outrigger system should be located at approximately half height of the building, that the outriggers in a two-outrigger system should be located roughly at one-third and two-thirds height, and that in a three-outrigger system they should be at approximately one-quarter, one-half, and three-quarters height, and so on. Generally for the optimum performance of an n-outrigger structure, the outriggers should be placed at the l/(n+l), 2/(n+l), up to the n/(n+l) height locations.

The Smith and Coull study found that the reduction in core base bending moment is approximately 58%, 70%, 77% and 81% for one-outrigger, two-outrigger, three-outrigger and four-outrigger structures, respectively. Unexpectedly, contrary to a traditional location for outriggers (Shueller 1977), they found that it is structurally inefficient to locate an outrigger at the top of a building. In an optimally arranged outrigger system, the moment carried by any one outrigger is approximately 58% of that carried by the outrigger below. However, if an additional outrigger is placed at the top of the building, it carries a moment that is roughly only 13% of that carried by the outrigger below, which clearly shows the inefficiency of this outrigger location.

2. Outrigger system

A braced frame with outriggers is shown in Figure 1 together with its deflected shape resulting from lateral loading. The structure comprises a centrally located braced frame with a particular bracing system which is connected to two equal-length outriggers. The bracing system of these outriggers may have a different configuration. The behavior of such a steel structure is similar to that of a concrete wall with outriggers. The deflected shapes of the vertical and horizontal members show the stiffening effect of the outriggers. The columns in the façade of the structure resist further rotation of the outriggers. The induced compression and tension forces in these columns create a large resisting moment to the applied horizontal loading.
In the analysis of outrigger-braced walls it has been shown (Stafford Smith and Salim, 1998; Stafford Smith and Coull, 2002) that the horizontal deflection behavior of the concrete wall can be represented by a single bending stiffness parameter, thereby assuming that the deformations in the concrete wall due to shear forces can be neglected. It was further assumed that the outriggers consisted of prismatic members which were rigidly connected to the wall and pin connected to the exterior columns and could thus be represented by a single bending stiffness parameter. In the analysis the columns were also assumed to be pin connected to the foundation. With three stiffness parameters representing the wall, outriggers and the columns it was possible to combine them in a single dimensionless parameter which allowed a rapid graphical procedure to determine the optimum location of the outriggers up the height of the structure in order to cause the largest reduction in horizontal deflection at the top of the structure. This method forms the base for the suggested analysis of braced frames with outriggers.
In the structure in Figure 3 the outriggers are shown as storey height trusses. The assumed in-plane rigidity of the floor structures will cause identical rotations in the braced frame and façade columns at outrigger level. It is taken that the riggers are attached to the braced frame and exterior columns only, thereby allowing double curvature in the outriggers to take place. The forced double curvature will increase its flexural stiffness. The horizontal and vertical trusses cannot be accurately represented by a single stiffness parameter. The deflected shape of a truss is not a function of bending only as a result of axial strain in the columns but will allow additional deformations due to strain in the diagonal members, i.e. racking. It has been shown (Hoenderkamp and Snijder, 2002) that the racking shear deformations and double curvature in the outriggers can quite easily be included in the existing method of analysis. It also allows the use of the existing design graphs without additional curves. The method was further developed (Hoenderkamp and Snijder, 2005) to include braced frames with façade riggers.
Braced frames with outriggers increases the complication of the analysis as the outriggers are forced to deflect with the braced frame which will be subject to bending and racking shear deformations. The assumption for concrete walls in which the shear deformations have been neglected, i.e. plane sections remain plane, does not hold for braced frames. The simple wide column behaviour applied to concrete walls cannot be assumed for trusses.

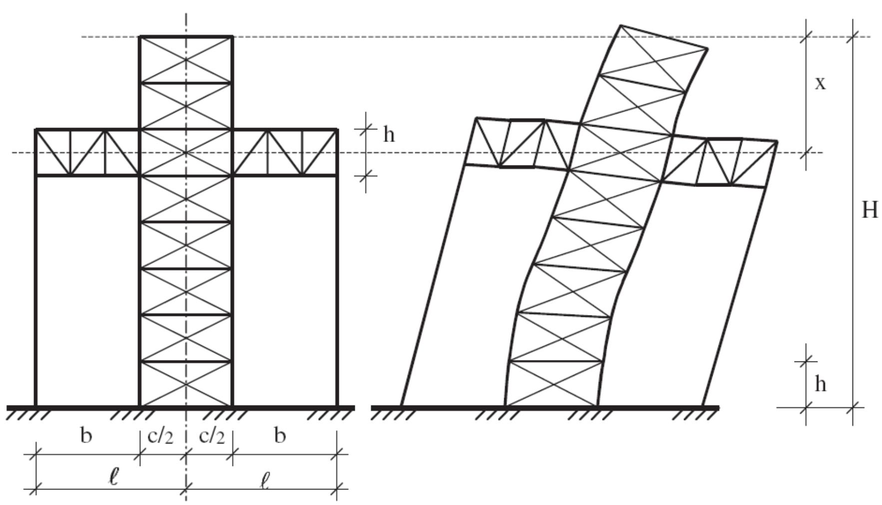

Figure 3. A schematic view of frame with outriggers

3. Equation of Outrigger Structures

A outrigger braced structure is essentially an outrigger braced structure where the horizontal stiffening outrigger structure is detached from the interior walls or cores and moved parallel to the outrigger structure of the building. The advantages of this location of the riggers are that all columns in the two end-outriggers will now participate in resisting the horizontal load on the structure and the floor lay-out obstruction of the outrigger structure has been removed. Since the behavior of both structures subject to lateral loading is similar, the analysis of outrigger braced structures will be explained briefly before it is extended to include outrigger braced structures.
The outrigger braced structure in Figure 4 shows a shear wall with rigidly connected outriggers. At the outer ends they are connected to the foundation through the exterior columns. When subjected to horizontal loading, the wall and outriggers will rotate causing compression in the downwind column and tension in the column on the upwind side. These axial forces will resist the rotation in the wall.
A simplified method of analysis of this structure has been presented earlier (Stafford Smith and Coull, 1991; Stafford Smith and Salim, 1981). It was assumed that the structure behaves linear elastically, columns only carry axial forces and that the sectional properties of wall and columns remain unchanged up the height of the structure. The salient equations of this method are repeated here in a different form as they will be used for the analysis of fac¸ade rigger braced structures.
The maximum deflection at the top of the structure consists of two terms: the free deflection of the wall subject to the full horizontal loading and a reduction term representing the decrease in lateral deflection due to the restraining moment formed by the axial forces in the columns.

$$y_{\max} = \frac{wH^4}{8EI_w} - \frac{M_c(H^2 - x^2)}{2EI_w} \tag{3.1}$$

in which w is a uniformly distributed lateral load, H is the total height of the structure, E is the modulus of elasticity, I_w is the second moment of area of the wall and x represents the distance measured from the top. The restraining moment on the wall is

$$M_c = \frac{w(H^3 - x^3)}{6EI_w}\left\{\left(\frac{1}{EI_w} + \frac{2}{EA_c\ell^2}\right)(H - x) + \left(\frac{\ell}{12EI_o}\right)\right\}^{-1} \tag{3.2}$$

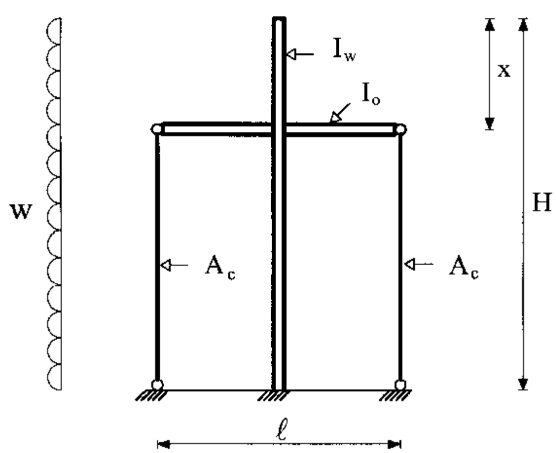

Figure 4. Outrigger braced structure

where A_c is the sectional area of the column, ` is the distance between the columns and EI_o is the bending stiffness of the outrigger. Introducing flexibility parameters for vertical and horizontal structure, respectively,

$$S = \frac{H}{EI_w} + \frac{H}{EA_c\ell^2/2} \tag{3.3}$$

$$S_1 = \frac{\ell}{12EI_o} \tag{3.4}$$

yields an expression for the maximum horizontal deflection at the top of the building

$$y_{\max} = \frac{wH^4}{8EI_w} - \frac{w(H^3 - x^3)(H^2 - x^2)}{12EI_w}\left\{\frac{H}{EI_w\{S(H-x)+HS_1\}}\right\} \tag{3.5}$$

By maximizing the reduction term of the deflection equation it is possible to find the optimum location of the outrigger and to present this in graphical form with a single parameter defining the deflection behavior of the outrigger braced structure; see Figure 5.

$$\omega = \frac{S_1}{S} = \left\{\frac{\ell}{12EI_o}\right\}\left\{\frac{H}{EI_w} + \frac{H}{EA_c\ell^2/2}\right\}^{-1} \tag{3.6}$$

It was also shown (Stafford Smith and Coull, 1991; Stafford Smith and Salim, 1981) that with this parameter it is possible to locate the optimum positions of two, three or four identical outriggers along the height of the structure. Graphs for these cases were also developed and additional diagrams were produced for moment reduction efficiencies and drift reduction efficiencies (Stafford Smith and Coull, 1991; Stafford Smith and Salim, 1981).

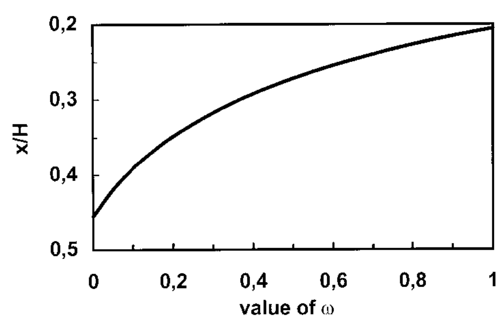

Figure 5. Optimum location of outrigger

4. Case Study
4.1. Vanak's Park Building

A 80-story steel-framed office tower will be used to investigate the effectiveness of belt trusses as virtual outriggers. This building does not represent a particular real structure that has been built or proposed. However, the dimensions, general layout, and other characteristics have been selected to be representative of a building for which the use of outriggers would be a plausible solution. Designs with conventional outriggers and virtual outriggers will be compared. The floor-to-floor height is 4 meters. The building has three sets of 4-story deep outriggers: between Levels 77 and 73 (at the top); between Levels 46 and 50; and between Levels 21 and 25.
The floor is 45 meters square and has a 15 meters square core at center. The span from the core to the exterior columns is 15 meters. The lateral load-resisting system consists of bracing at the walls of the 15 meters square core and the three sets of outriggers indicated in Figure 6.

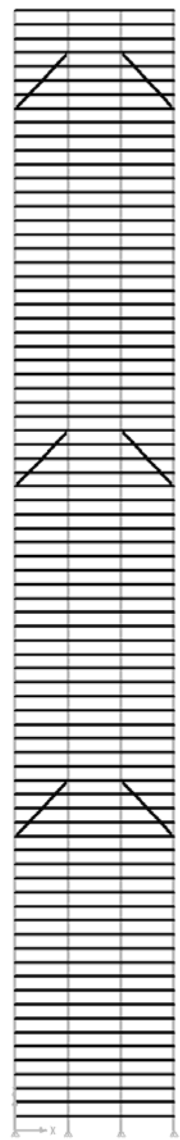

Figure 6. Elevation of building

Columns along the exterior edges of the tower are at 10 meters centers. The 15 meters square core has columns at the corners and at the center, to create 10 meters spans for the floor framing within the core. There is no column at the center of each 15 meters side of the core, since the braced frame that constitutes the side of the core can easily support dead and live loads across a 15 meters span. (This arrangement places more than 90 percent of the core column steel and 90 percent of the core gravity load at the corners of the core, where the steel area and gravity load are most useful for resisting lateral loading on the tower.) With work points for the core bracing diagonals set at the top of the horizontal members, there is adequate clearance under each inverted "V" of diagonal bracing for access to the elevator lobbies in the core.
All connections are simple shear connections; there are no moment connections. Typical floor slabs consist of 1 meters of lightweight concrete over 5 cm composite metal deck.

4.2. Design Loads
Design loads are in accordance with Iranian Building Code. The design wind load, applied on the projected elevation of the building, varies from 100 kg/m^2 at ground level to 200 kg/m^2 at the top.

4.3. Member Sizes

Members were proportioned with enough accuracy to provide a reasonable indication of the behavior of the structure and the effectiveness of the outriggers. The general approach was to size members for the structure with conventional outriggers, and then to retain the same sizes for the design with virtual outriggers. This allows direct comparison of the two outrigger systems. Stresses were checked at a few locations in the design with conventional outriggers, but there was no exhaustive code-checking of members.

The eight "supercolumns" (the columns engaged by the conventional outriggers) have a cross sectional area of 7500 cm^2 at the base of the building. Other exterior columns have a maximum area of 1800 cm^2. The columns at the four corners of the core have an area of 5500 cm^2 at the base. Column sizes decrease over the height of the building to about a quarter of the maximum near the top. All column sizes and core bracing member sizes are the same with both outrigger types. The outrigger truss members are about the same size in the conventional and virtual outrigger designs (except that the diagonals in the chamfered corners of the belt trusses are smaller). Typical truss members are very large W14 sections in the lowest set of trusses; the other trusses are somewhat lighter.

Specially strengthened floor diaphragms are required at the top and bottom of each virtual outrigger, to transfer horizontal force from the core to the chords of the belt truss. The slab is 25 cm thick, including the metal deck, at the lowest truss (at Levels 21 and 25), 20 cm thick at the second truss (at Levels 46 and 50), and 15 cm thick at the upper truss (at Levels 73 and 77). Regular-weight concrete is used in these slabs.

4.4. Method of Analysis

The building was analyzed as a three-dimensional elastic structure, using the ETABS computer program. In the modeling of the floors at the top and bottom of each outrigger, beams were represented by line members and the slab by planar finite elements. Foundation deformation was neglected in the analysis; columns were assumed to be mounted on non-movable supports at the base.

4.5. Results and Evaluation

The lateral displacement at the top of the building due to wind loading was found to be 70 cm for the design with conventional outriggers and 95 cm for the design with belt trusses as virtual outriggers. The structure was also analyzed with no outriggers at all (and no change in core member sizes). The displacement increased to 275 cm. The structure with virtual outriggers was analyzed with a ten-fold increase in the in-plane stiffnesses of the floor slabs at the top and bottom of each belt truss. The displacement decreased to 80 cm. When, in addition, the belt truss member sizes were increased ten-fold, the displacement decreased further to 65 cm.

5. Summary and Conclusions

Techniques for using belt trusses and basements as outriggers in tall buildings have been proposed. Belt trusses used as virtual outriggers offer many of the benefits of the outrigger concept, while avoiding most of the problems associated with conventional outriggers. Basements used as outriggers can create a wider effective base for resisting overturning. The application and effectiveness of belt trusses as virtual outriggers has been demonstrated through an example. It is clear from the example that the outrigger concept works as intended. However, with the same outrigger column sizes and locations, virtual outriggers will be less effective than conventional direct outriggers because of the reduced stiffness of the indirect force transfer mechanism. In many applications, the reduced effectiveness or efficiency of the outrigger system will be more than compensated for by the following benefits offered by the proposed concept:

1. There are no trusses in the space between the core and the building exterior.
2. There are fewer constraints on the location of exterior columns. The need to locate large exterior columns where they can be directly engaged by outrigger trusses extending from the core is eliminated.
3. All exterior columns (not just certain designated outrigger columns) participate in resisting overturning moment.
4. The difficult connection of the outrigger trusses to the core is eliminated.
5. Complications caused by differential shortening of the core and the outrigger columns are avoided. In the lateral load analysis of a building with the proposed outrigger system, the in-plane stiffness of the floors that transfer horizontal forces from the core to the outriggers should be modeled accurately. These floors cannot reasonably be idealized as rigid diaphragms.

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