“Use and Detailing of Outrigger Bracing Systems for Reducing Drift and Base Moments in Tall Buildings”

1.0 Abstract/Introduction:

As the design of tall buildings has evolved in recent decades, the need for more efficient lateral bracing systems has grown out of the demand for taller buildings with more useable interior space. Coupled structural wall cores, which are efficient for laterally bracing mid-height structures (roughly 30-40 stories), become inadequate for laterally bracing taller structures. It is possible, however, to overcome this limitation by increasing the flexural depth of taller buildings by bracing the stiff core against the perimeter columns of the structure. This is often achieved by incorporating very stiff, often massive, elements referred to as outrigger beams over the height of the structure. Through the interaction of the flexural stiffness of the structural wall core and the axial forces in the perimeter columns acting around the centroid of the structure, the drift is then diminished and the transfer of base moment is dispersed over a larger area of the building's foundation.

The design of these outrigger beams presents the structural engineer with several interesting design challenges. These issues range from selecting the optimal vertical placement of the beams, to compensating for relative creep, shrinkage, and temperature effects between the inner core and perimeter columns, to dealing with considerable congestion of reinforcement. Despite these challenges, outrigger bracing systems have been successfully incorporated in the design of some of the tallest buildings in the world. This paper first discusses some case studies of tall buildings which have advantageously incorporated outrigger beams in their design, and then explores some of the solutions which have been proposed in the literature and implemented in the field for solving these various design challenges.

2.0 Discussion of Case Studies:

Several of the tallest structures constructed in recent years have relied on a structural wall core and outrigger bracing system to control lateral drifts. For example, the striking 88-story Petronas Twin Towers located in Kuala Lumpur, Malaysia, completed in 1998, incorporated an outrigger bracing system. These massive beam-wall elements occupy floors 38 through 40 of the towers, and link a central core to a "ring beam" around the perimeter of the structure which engages all 16 of the massive perimeter columns to increase the flexural rigidity of the structure. As a result, the base moment transferred through the wall core to the foundation was reduced by 50%. Furthermore, lateral deflections of the structure were sufficiently controlled by this lateral bracing system so as to not warrant any supplemental damping [11].

The 84-story World Tower in Sydney, Australia, which was completed in 2004, is also designed with an outrigger bracing system intended to control lateral motions. The very slender building, with a height to base width ratio of 9:1, required that the concrete structural wall core be braced by 20 high-strength reinforced concrete perimeter columns through the use of outriggers. Connell Mott MacDonald, the structural engineers, chose a unique eight story high diamond shaped post-tensioned outrigger wall system. These elements, located at mid and three-quarter height, connect the wall core to "spreader walls", which engaged all of the perimeter columns on each face of the structure. This system transfers 70% of the total base moment to the perimeter columns and provides sufficient lateral rigidity to eliminate the need for expensive supplemental damping systems [3].

A final example of the successful implementation of this structural system is currently under construction in Chicago, Illinois. Scheduled for completion in 2009,

Figure 1: Trump Tower Outriggers, (from reference [1])

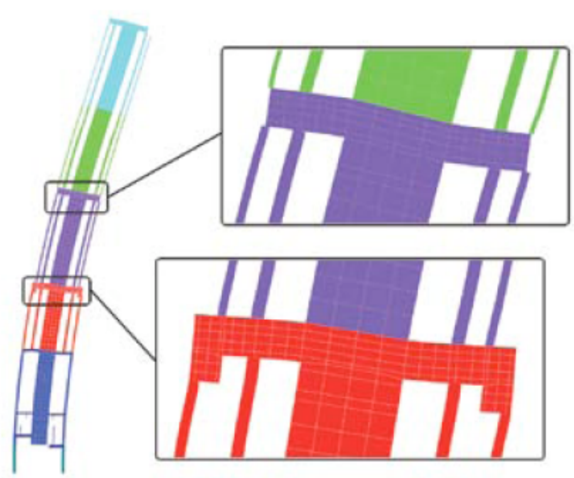


Fig. 3: The outrigger wall-beams engage perimeter columns to significantly increase the effective width of the lateral system

the Trump International Hotel and Tower will reach 92-stories, and will be the tallest reinforced concrete building in the US. This structure is very slender, with an aspect ratio of 8:1. This requires, similar to the previous cases, that the central wall core be braced by the perimeter columns to reduce base moment and control drift. Outrigger elements located at levels 28-29, 50-51, and 90-91 (see figure 1), connect the central core to "belt walls". These walls engage all the columns along the perimeter of the structure, and tend to equalize the column loads. The improved stiffness provided by this structural scheme, in addition to the increased mass and damping inherent in concrete frame structures, again negates the need for any supplemental structural damping systems [1].

3.0 Preliminary Structural Modeling for Feasibility and Placing of Outrigger Systems:

Outrigger bracing systems are primarily intended to accomplish two purposes: reducing the percentage of total base moment transferred from the structural wall core to the foundation, and limiting the lateral drift of the structure. It has been shown that outriggers placed near the bottom of the structure are most effective for reducing base moments, while outriggers placed nearer to the top or two-thirds of the structure are more effective for controlling deflections [7]. It is also widely acknowledged that due to diminishing returns from placing additional outrigger elements, it is rarely reasonable to incorporate more than four outrigger beams in a single structure [8]. Therefore, the task of selecting the location for outriggers in a structure can theoretically become an interesting optimization problem of balancing which aspects of structural behavior are most critical for the building under consideration.

In 1985, Moudarres [5] published an analysis of a generalized structure with one outrigger placed at the top floor. The model was based on basic equilibrium and compatibility, in which the axial forces in the perimeter columns, the imposed internal axial forces in the structural walls, and the internal moments imposed by the outrigger on the structural walls were considered. Equations were derived which numerically demonstrated the relative effect of various parameters on structural response to various loading schemes. Although the derived method is entirely valid, it is too complex to be reasonably employed in the design of tall structures, and so it is not included here in detail. Rather, the most telling conclusions drawn from the analysis will be discussed.

Moudarres [5] showed that while a single outrigger placed at the top of a structure may be expected to influence the structural wall moment at the top of the structure by as much as 30%, it will likely not reduce the base moment resulting from a triangular load by more than 10%. In comparison, that same outrigger, still placed at the top of the structure, may reduce lateral roof drift by as much as 37% for that same triangular load. This finding supports the conclusion that placement of outriggers near the top of the structure can be of significant help for controlling drift, but is much less efficient for reducing base moments in the structural wall core. The study also showed that while the ratio of column area to wall area was a critical parameter for drift reduction at very low ratios, increasing column area beyond a ratio of roughly .10 has a somewhat negligible effect on the total system behavior. At these larger column-to-wall stiffness ratios, the controlling variable becomes the flexural rigidity of the outrigger element itself, reflected in this study by the ratio of the distance between the wall and the column axis to the clear distance between the coupled walls. A final general conclusion which may be drawn from this study is that an outrigger element placed at the top of a structure is most effective in response to a point load near the top of the structure, and least effective in response to a uniformly distributed lateral load. Structural response to triangular loading is only slightly better than for uniform loading [5].

A more general study, which provides design charts for locating the optimum outrigger placement for controlling drift in a structure resisting uniform wind loads with up to four outriggers, was published in 1981 by Smith and Salim [9]. Key assumptions made by the authors included linear elastic behavior of all elements, a rigid foundation, and uniform member sizing throughout the height of the structure. This last assumption was argued to be valid since the overall structural response is largely dominated by the section properties at the base levels. Thus the section properties at the base of the structure should be used in this preliminary analysis rather than some sort of average member size. Figure 2 [10], shows the general model used by Smith and Salim in their formulation. The effect of reducing the moment in the core is clearly depicted by this diagram, as is the notable reduction in roof drift, which can be estimated by using the moment-area method. Appendix 1 includes sample design charts presented by Smith and Salim [10] which express the optimal location of up to four outrigger elements for the

Figure 2: Deflection and moment distributions in a structure braced by a single outrigger, (from reference [10])

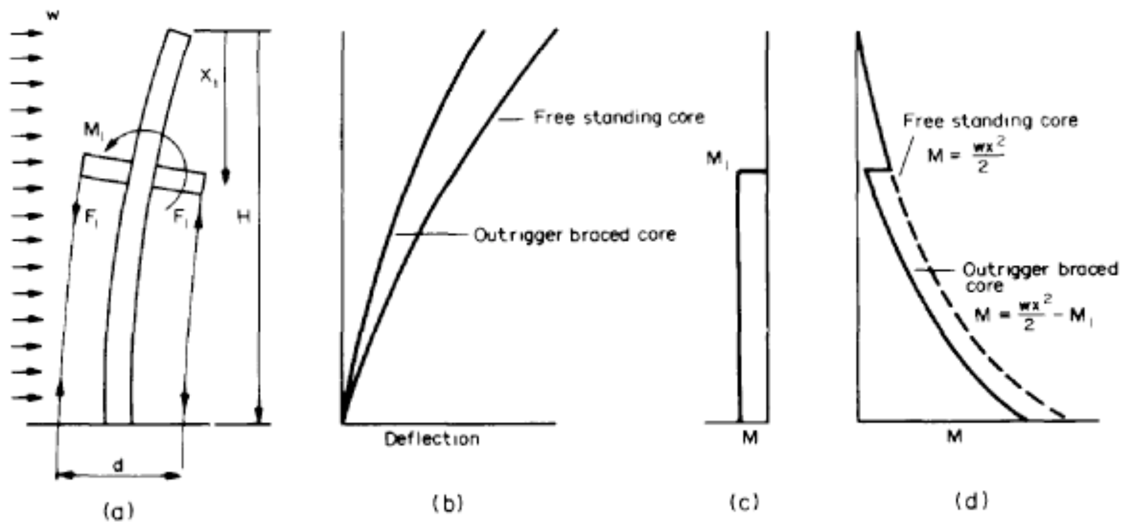


Fig. 1(a) One-outrigger structure. (b) Deflection diagram. (c) Restraining moment diagram. (d) Resultant bending moment diagram for core.

control of lateral roof level drift. These curves are presented as a function of α, representing the core to column inertial ratio, and β, representing the core to outrigger inertial ratio. It can be generally concluded from the design charts presented that for stiffer outrigger beams and perimeter columns, the resulting optimum placement for outrigger beams tend to be at lower levels than for softer systems. In addition, the authors present design charts which express the efficiency of the selected system for reducing drift and base moments. These charts show that stiffer systems are more efficient at reducing both base moment and lateral drift, whereas softer systems tend to require higher outrigger beam placement for optimum drift control, and are therefore less efficient at controlling base moments [9].

For comparison, another approach was published in 1989 by Coull and Lau [2] which endeavored to further generalize design charts previously discussed to any number of outrigger beams by smearing the bracing effect over the entire height of the structure. To use the charts provided by the authors, an effective smeared outrigger stiffness must be determined for the structure under consideration. Then the charts may then be used to predict the system's efficiency for reducing base moment and drift. The charts show possible drift reduction of beyond 90% for infinitely stiff bracing elements smeared over the entire structure, which could be likened to essentially filling the entire structure with concrete. Despite the impracticality of the limit case, the general method was shown to be in good agreement, even for the case of a single outrigger beam, with previously developed models [2].

Despite the carefully derived methods for selecting the optimum placement of outrigger beams discussed above, it should be noted that these methods should best be interpreted as revealing general structural trends rather than being used as a final design tool. Smith and Salim concede that once the design is beyond the preliminary stages, a more advanced stiffness analysis should be used for determining the actual drift and base moment reductions in lieu of their guidelines [9]. It is also important to note that the outrigger system, although effective for reducing base moments in the wall core and limiting lateral deflections, does not enhance the structure's capacity for transferring base shear to the foundation. The structural wall core must still be designed to transfer the base shear, in its entirety, to the foundation [8].

Finally, it should be noted that the above studies implicitly assume that the structural engineer contributes substantially to the final building layout, despite the fact that this is often not the case. Often, as a result of their massive size, outrigger elements are placed only on mechanical floors in tall buildings. The location of these mechanical floors is often set early on in the design process with little input from the structural engineer. Ultimately, it is up to the engineer to optimize the lateral bracing system within the architectural constraints provided [7].

4.0 Detailing of Outrigger Elements:

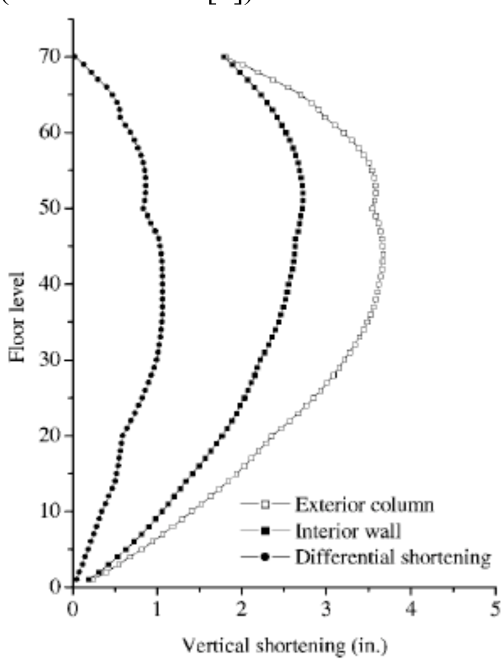
Once the location of outrigger elements is selected, and preliminary sizing of structural members has largely been completed, the engineer is confronted with two, often significant, design challenges regarding the sizing and detailing of the outrigger beams. In addition to transferring significant internal axial loads and moments from the structural wall core out to the columns as axial loads, the outrigger beams are significantly affected by differential creep and shrinkage strains between the perimeter columns and core. The massive and highly stiff outrigger beams must be designed to sustain the significant loads which can result from the small displacements imposed by these differential strains. To further complicate matters, despite the massive size of the outrigger elements, congestion often becomes a significant challenge for engineers and construction personnel to overcome.

4.1 Creep and Shrinkage Compensation:

A common engineering problem in the design of tall structures derives from the fact that creep and shrinkage strains in the perimeter columns differ in comparison to those in the structural wall core. The differences in volume to surface ratio, reinforcement ratio, and especially axial stress, result in occasionally significant relative displacements at the upper levels of a structure. This relative displacement can cause serviceability issues in flexible slab systems, where a gradual descending slope can develop from the central core out to the perimeter of the structure. The problem is exacerbated in very stiff elements like outrigger beams, where relative vertical displacements translate into significant loads.

Accurately predicting these strains at all points in time can become an immensely complex problem. These complexities are most pronounced early on when creep and shrinkage are most quickly changing, and where dead loads are continuously and incrementally applied to the structure throughout the construction sequence. To complicate this further, the maturity of the concrete, and therefore the strength and stiffness, varies with every constructed floor. Note the significant vertical differences developed in an example 70-story structure shown in figure 3 [6].

Figure 3: Relative vertical shortening in a
typical 70-story structure,
(from reference [6])



In 2003, H. S. Park [6] discussed a gradual compensation approach similar to that proposed in 1984 by Fintel, Ghosh and Iyengar, where material creep models are used to predict relative displacements between the structural core and perimeter columns. Then, required correction factors are calculated and specified to be built into each floor such that each column is constructed with a pre-specified positive error to compensate for the inevitable negative error to come with time. To ease construction efforts, groups of floors with similar predicted relative errors are lumped together and assigned a common correction factor [6]. A similar correction scheme has been adopted in the design of many tall buildings, but additional measures must be taken to account for the significant internal stresses which these displacements will impose on the stiff outrigger elements.

In the design of the World Tower in Sydney, several steps were taken to avoid these additional stresses on the outrigger beams. First, high-strength concrete, with its associated higher modulus, was used in the perimeter columns to reduce creep. In addition, as proposed by Park and others, each floor was constructed slightly higher at the perimeter than around the core to compensate for the eventual shortening of the exterior columns. Finally, as a complement to these typical procedures, additional measures were taken to avoid overloading the outrigger beams. These additional measures took the form of adjustable oil-filled jacks used at the interface between the outrigger wall-beams and the “spreader walls”, to allow for adjustments to be made early on while the majority of the creep and shrinkage is taking place. This last step is somewhat unconventional, but was deemed necessary by structural engineers to control loads imposed on the outrigger beams [3].

In the design of the Trump International Hotel and Tower in Chicago, the problem was likewise taken very seriously, but was approached very differently by the team of engineers. Eight separate finite element models were developed representing the entire structure at eight different periods in time. An effort was made to account for a wide range of time-dependant effects including creep, shrinkage, construction sequencing, and varying material properties. These models were used to predict the loads which would be imposed on the outrigger beams and transferred to the structural core due to this differential shortening at all key periods of time. Rather than trying to compensate for the differential shortening through the use of jacks, the outrigger beams and structural core were designed to directly withstand these additional loads [1]. In addition, although not expressly intended as compensation for these time dependant strain effects, it was specified that each new floor be constructed to its theoretical height rather than some regular distance from the previous floor. This will inevitably have some compensating effect similar to that proposed by Park, although it would not be sufficient alone to fully account for creep and shrinkage effects in an outrigger system [7].

It should be noted that in addition to the inherent complexity of this strain problem stemming from the fact that the solution relies on the accurate prediction of several highly time dependent variables, the basic shrinkage and creep models adopted by various codes including the ACI, CEB, and PCA codes are merely approximations themselves. Various authors have discussed this additional source of variability; for example, field strain measurements were performed on a typical 69-story structure [4], which at times showed remarkable agreement with predictions, while at other times significant deviation from predictions were revealed. Figure 4 shows field strain measurements in a structural wall which show evidence that the prediction equations are conservative. Figure 5, although the error is not egregious, shows evidence of un-conservative predictive behavior by the code equations. This brief discussion of model uncertainty is intended mostly to highlight the fact that designers should handle shrinkage and creep predictions with care when they have significant bearing on the integrity of the structure, as is the case with outrigger braced structural wall cores.

Figure 4: Measured and calculated strains in structural wall 1 of a 69-story structure (from reference [4])

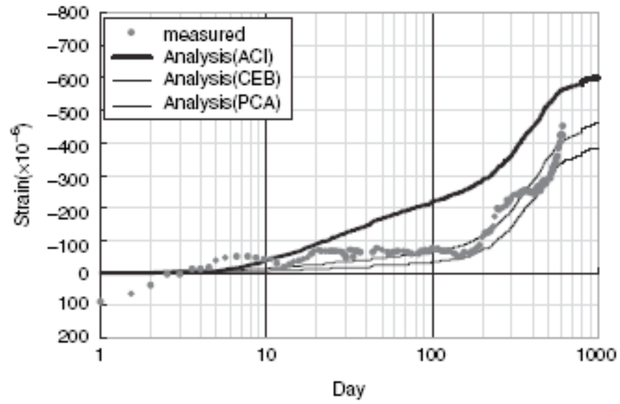


Figure 13. Measured and calculated strains of W1 at level 4

Figure 5: Measured and calculated strains in structural wall 2 of a 69-story structure (from reference [4])

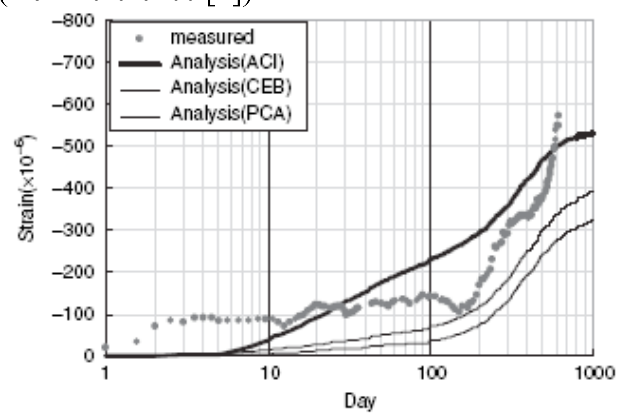


Figure 14. Measured and calculated strains of W2 at level 4

4.2 Reducing congestion:

Once the engineer is satisfied that loads resulting from dead, live, and other sources such as creep and shrinkage strains have been largely accounted for, the challenge becomes designing an outrigger element which can withstand this loading over time. As an added challenge, retaining the design stiffness of the outrigger element is of primary importance for maintaining the lateral stiffness of the structure and controlling lateral drifts to within serviceability requirements over the long-term. This requires that sufficient reinforcement is provided for the concrete to not only withstand the applied loads, but also largely control cracking of the element. In recent practice, strut and tie models have been relied on to design both the critical outrigger beams and the directly adjacent structural wall regions. Despite the massive size of these elements (up to 66 in. wide and 17.5 ft. deep in the case of the Trump International Hotel and Tower), mitigating congestion of the steel reinforcement becomes another significant challenge for the engineer to solve [1].

Conventional solutions to this problem are often employed, including the use of high-strength and high-performance materials. In the case of the Trump International Hotel and Tower, 75 ksi longitudinal steel reinforcement and 16 ksi self-consolidating concrete were used in all of the outrigger-structural wall connection regions. Also, end terminators were specified in many regions rather than 90 degree hooked anchorages to again limit the amount of congestion [1]. In regions where these solutions still were not sufficient, a very uncommon solution was specified for the Trump International Hotel and Tower. In the most congested areas, 70 ksi steel plates with welded shear studs were specified as the longitudinal reinforcement. Despite introducing an additional trade to the construction site, and requiring complicated field welding of splices for long plates at great heights, this was regarded as the most viable solution to congestion problems [7].

A notable exception to this great difficulty in dealing with reinforcement congestion in outrigger braced structural wall systems is the World Tower in Sydney. The original design of the outrigger elements as 8-story high diamond shaped post-tensioned walls resulted in far less critical connection regions. The result is a reinforcement scheme consisting primarily of large conventional steel bars [3].

5.0 Summary/Conclusion:

First used in 1962, outrigger beams have become a primary design option for engineers of tall building structures as a scheme to more efficiently use existing structural wall and column capacities to laterally stiffen structures and dissipate base moments [9]. Several studies have been conducted to evaluate the relative importance of various parameters and develop design guidelines for efficiently placing outrigger bracing elements over the height of the structure. Design charts and guidelines have been developed for help with initial placement, but more precise modeling is required for evaluation of lateral drift and core base moments reduction. It bears repeating that outrigger bracing systems do not augment the structural capacity for transferring base shear to the foundation beyond the capacity of the structural core alone.

When designing outrigger bracing systems, engineers must seriously consider differences in axial shortening between the structural wall core and perimeter columns largely due to creep and shrinkage effects. Although a variety of solutions have been proposed and adopted, the conclusion is that the very stiff outrigger wall-beams are significantly affected by even small relative displacements. Measures must be taken to mitigate these effects, which are complicated by the substantial variability of the input parameters and the only approximate accuracy of the models themselves.

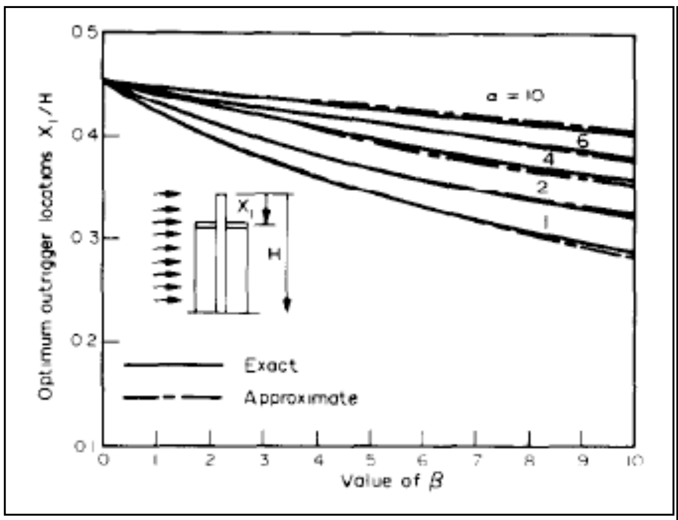
Finally, in order to adequately ensure the significant load carrying capacity and stiffness of the outrigger wall-beam system, steps must be taken to simplify detailing in the most critical regions. Regardless of whether the design firm chooses to adapt architectural building plans to allow for larger elements, or replace longitudinal steel with high-strength welded steel plates, solutions must be sought to mitigate reinforcement congestion.

Ultimately, in recent years, the practicality and efficiency of outrigger braced structural wall systems have been numerically derived and evidenced in practice. The detailing of the critical bracing elements does not come without challenges for engineers, but these have proven to be solvable with various creative design solutions.

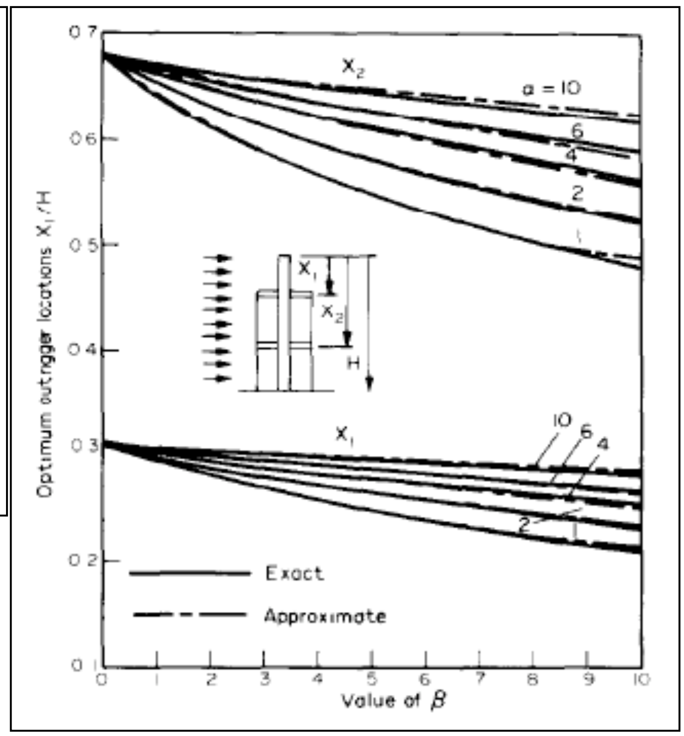
Appendix 1:

Design guides presented by Smith and Salim [10] for locating the optimum placement of up to four outrigger beams for greatest control of lateral roof drift. These curves are presented as a function of α, representing the core to column inertial ratio, and β, representing the core to outrigger inertial ratio. Note that separate charts [9] (not included here), were presented which offer a rough prediction of the efficacy of the selected outrigger braced structural core system for controlling drift and core wall base moment.

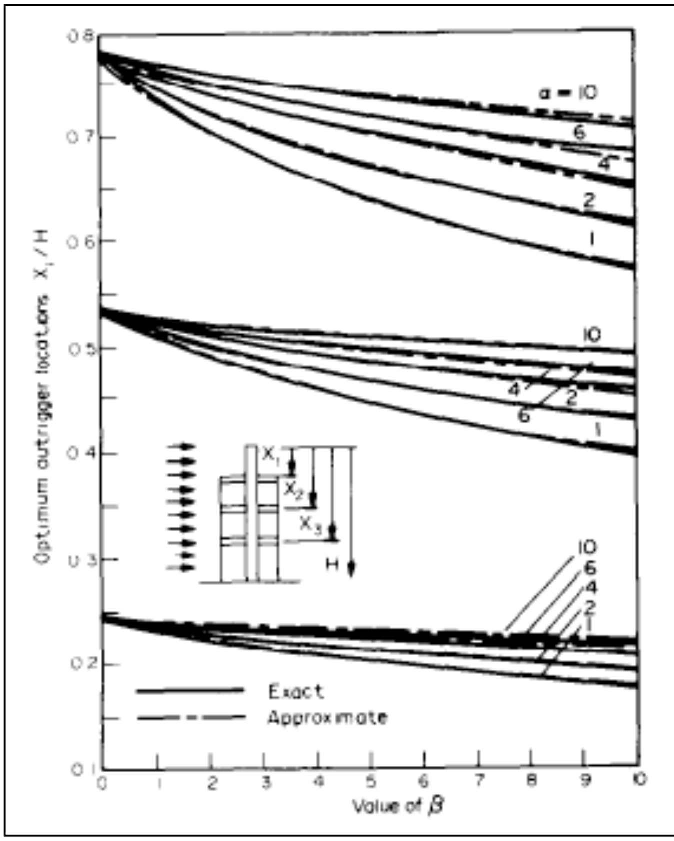
One outrigger:



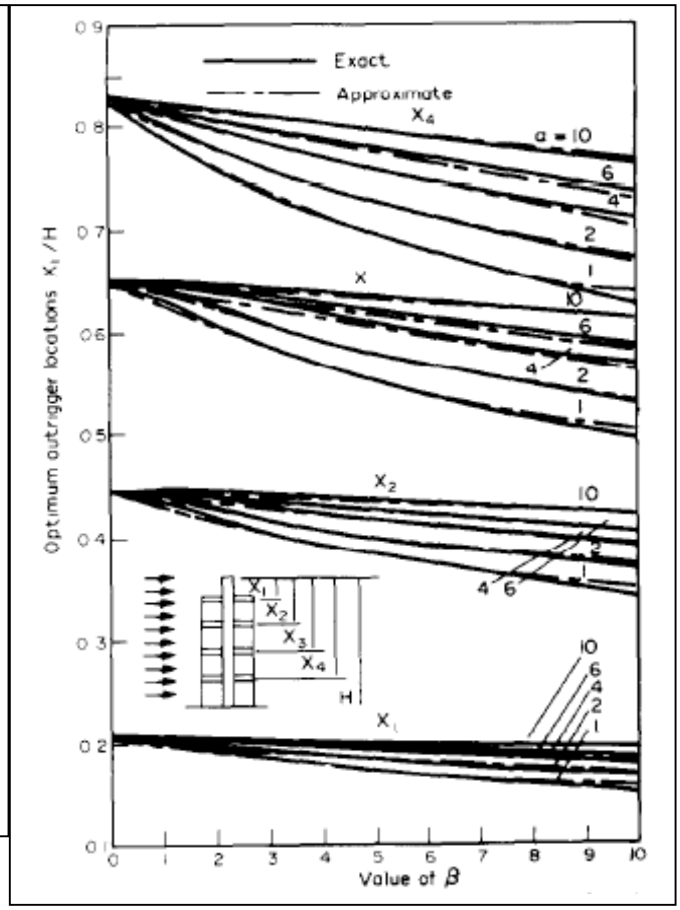
Two Outriggers:



Three Outriggers:



Four Outriggers:



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