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A Dynamical Approach to Structural Design And Development of Super-Tall Slender Buildings Based on Multiple Hollow-Tube Concept: Part I Theoretical Development

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ABSTRACT

This paper presents the development and theory of the Multiple Hollow-Tube (MHT) system and its idealised spring behaviour for a subject super-tall building with an aspect ratio 12:1. A dynamical approach is proposed herein to quantify the mechanical behaviour of super-tall buildings as varying states of stiffness and rotation capacity of substructures comprising the superstructure or mega frame. Further, the fundamental relationship between the condition of rigidity and flexibility for these constituent parts is resolved as a function of their interdependent relationship to the structure's global geometric connectivity from storey to storey. Optimum locations of stiffness can therefore be determined, discretizing the dispersion of moment leverage, while simultaneously enveloping it with optimum flexibility (spring-like movement), to meet the dynamical deformation demand induced by transient excitations. The developmental procedure of the MHT system incorporating the spring-truss technique is discussed in some detail.

INTRODUCTION

Increasing height and slenderness are common characteristics of modern super-tall buildings of this century (Smith and Coull, 1991). Indeed, the characteristics of modern city landscapes induce the taller heights of buildings by limiting the size of the footprint according to the net area of the subject site. Further, the mechanical and structural behaviour of slender super-tall

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buildings is inherently more dynamic than buildings of stockier proportions over shorter elevations (Skidmore, Owings and Merrill LLP, 2002). Hence, it is evident that static or quasi-static equivalent lateral analysis methods are insufficient for determining and describing the migration of forces over the height of super-tall structures and consequently the details of their structural design.

Dynamic analysis and design are essential in determining the behaviour of super-tall buildings, and subsequently develop a natural pattern for proportioning the structure such that the full vibrational benefits of the building's slenderness can be utilized (Foster and Partners LLP, 2001). As design proceeds, the evident vibrational characteristics of the alternating proportions derived from iterative dynamic analysis, can be refined and optimized to control and minimize the migration of shear forces and bending moments incurred by transient resonance. As the initial slenderness of the structure is refined according to migratory force envelopes, the global dynamic behaviour of the structure can be fine tuned and predetermined well before detailed structural design and analysis are executed. In addition, the ideal locations of lumping stiffness can be identified and used as an accurate convergence technique for rapidly locating core elements and other major stiffening elements analogously. It follows that secondary elements, such as columns, can thereafter easily be placed about the core elements as coupling lines for continuous outriggers.

Efficiently well applied dynamic analysis can therefore lead to the development of new hybrid structural systems for tall and super-tall buildings, which emulate the desired structural properties. Hence, the strengths and benefits of more complex building geometries can be utilized to develop an optimal structural system reflective of the obvious load path, rather than a preconceived one. In addition, dynamically evident properties of common structural systems, such as the deep outrigger truss, can be applied more intelligently in composite arrangements within the stiffening axis of slender tall buildings, inducing a continuity of response by imitating the reverse nature of the applied transient forces. Since the ability of a structure to vibrate under excitation depends upon its physical arrangement of mass and stiffness (Halliday *et al.*, 1997), the governing and most critical parameter for design remains the geometric arrangement of the structures form (Paulay and Priestly, 1992). The ability to control structural mass within the distribution of structural stiffness is therefore the primary aim of structural systems for super-tall slender buildings, and a constant variable against which geometric design is initiated.

Super-tall slender structures therefore require deformation control in terms of controlling the vertical distribution of mass, weaving in and out of the accelerating forces present at each storey (Perera, 2001). It follows that continuity of structural stiffness can be used to effectively control and dissipate deformation, by physically creating continuous elements over the full height of a structure. Rather than limiting stiffness to plan levels or points of large deflection within the buildings height, continuous uninterrupted spans of tightly knit webs or cages can be used to increase and evenly distribute the stiffness for optimum structural dissipation. Further, lumping vertical stiffness elements around the periphery and within the core of building plans, enables moment resisting lever-arms to be magnified in effect by the continuity of stiffness. By limiting the development of lateral forces over the structure's height by controlling structural mass at each storey, transient loads can be damped and inverted, redirecting the largest forces toward the structural base where the structure's greatest moment resisting lever-arm resides. Upon redirection, the building's overall centre of gravity, which is very low to the ground, dissipates vibration by reducing the global lever arm with which transient loads can activate the structure.

Hence ideal locations of added damping are self evident and easily fit within the structural orientation of stiffness at the point where maximum forces converge.

Hence, following these observations, a dynamical approach has been employed to develop analysis and design methods for new structural technologies attuned specially for super-tall slender buildings. Presented herewith, is the application of the MHT concept incorporating the spring-truss technique to super-tall slender buildings by adopting a hybrid dynamical design/analysis approach to quantify the mechanical behaviour of the system under seismic loads. The concept and design approach are demonstrated by applying the principles to a subject super-tall slender building of relatively simple geometry, in three parts: viz. the MHT system, the dynamical design and analysis approach, and the preliminary theoretical seismic behavioural results. Finally, the implications of the approach and its effective application to very slender buildings of all heights are examined in some detail, in addition to the establishment of a developmental procedure capable of more sophisticated hybrid design techniques for conceiving super-tall slender building structures.

THE MULTIPLE HOLLOW-TUBE (MHT) CONCEPT

Background

The Multiple Hollow-Tube (MHT) concept has been based upon the percept of structural dynamics that observes continuous and evenly distributed stiffness in structures to produce an inherent capacity for vibrational dissipation. In addition, a natural fundamental behavioural characteristic of very tall slender buildings, a substantially slower mode of vibration, has been exploited to reveal an idealized structural arrangement that meets dynamic response requirements. The principles of structural dynamics have been used qualitatively to evolve the principles of structural stiffness relative to the proposed structural system, ensuring that architectural and structural forms are analogous and one in the same. This technique for the analysis of super-tall buildings has been used as the primary tool for developing the MHT concept, enabling the dynamic and hysteretic nature of inelastic deformation of material systems of individual lesser strength to respond intelligently to forcing functions when combined efficiently. The quantitative descriptions based on historical and current research have been used as a tool for describing the preliminary mechanical behaviour of structures in their tallest range and the performance of existing structural systems after subjection to earthquake events. The Kobe earthquake that hit Japan in 1995 has been classified as one of the worst events to occur in recent times, approximating to a 1:2000 year event, and as such has been utilized as a focus for modern seismic research (Whittaker *et al.*, 2000). Furthermore, the presence and occurrence of maximum credible events has forced re-examination of international design codes regarding seismic performance criteria for tall structures in the elastic and inelastic domain, leading to subsequent tighter restrictions for structures in earthquake regions. Therefore the primary aim of the MHT concept is to evolve a structural system capable of responding to maximum credible earthquake events at extreme elevations and structural slenderness, and to identify the influence seismic forces have on super-tall structures.

Theoretical and mechanical development

The MHT concept is an extension of the principles of hollow tube box-sections, encompassing the individual behaviour of hollow tube sections with a minimum number of perforations in their peripheral walls to ensure that the distribution of bending stiffness is axially consistent and programmed purposely to couple against applied forces (Garfinckle and Pastore, 2003). In addition the restraint provided by multiple groups of tubes is exploited around the base plan of a structure and tapering its subsequent elevation to meet the tubes restraint at the structure's pinnacle. The base plan of a super-tall structure is depicted in Fig. 1, where the regularity of the plan is exploited by circular hollow tubes that are placed evenly along the façade and spaced at a distance equal to their outer diameter in series from each other. Considering the plan's geometric centre and the principal neutral axes passing through this point, it is readily observed that the tubes are symmetrical about both axes of the plan. The distance with which the tubes reside from the neutral axis in both directions is maximized by increasing the base width dimension of the plan until the sectional inertia of the whole base is maximized by the largest possible distance. Recalling that a tube resists bending by restraining the resultant tensile and compressive axial forces on either face of the walls (Beer and Johnston, 1992), the plan presented in Fig. 1 increases the axial resistance to earthquake loads by increasing the lever arm distance from the centroidal point of load contact to the peripheral tubes. Instead of the plan's peripheral walls being framed representations of a tubular wall, as is common with the framed tube concept, the peripheral stiffness is divided up and concentrated into definite locations at a clear distance from each other, inducing a lumped stiffness. Each cylindrical tube concentrates the bending and axial stiffness at a predetermined location in the structural plan ideal for distributing bending forces evenly across the tension and compression sides of the neutral axes, and transfer of these forces to axial actions in the spring-truss webs between them.

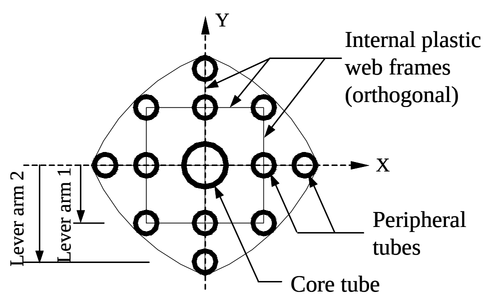


Fig. 1. Schematic layout plan of MHT system

The tubular sections undergo uniform axial stress due to bending load and provide restraint to each other when linked by the infinite in-plane stiffness of spring-truss webs. Further, the deformations experienced by the tubes are enforced to be equal by concentrating the largest bearing material closer to the plans outer corners as possible, reducing the tubular spacing in these areas of the plan to 85% of the tube's outer diameter. The regularity and symmetry of the floor plan ensure that earthquake forces act inertialy, passing forces through the centroid of each plan on every level, reducing the occurrence of torsional coupling within each storey to a minimum and accidental value as defined by design codes. Further, the interaction of forces within each tube is regulated by shear flow mechanisms that distribute the forces directly to the tubes in the elastic domain, increasing its elastic load threshold for frequently occurring earthquake events. Examining the layout of the tubes in the outermost corners of the plan reveals a spacing for the tubes that portrays a triangular modular pattern, connecting the four tubes that exist in this area with an isosceles triangle passing through their geometric centres. The effective group behaves as a rigid unit that undergoes compression or tension under lateral load, evenly distributing the stresses among themselves at every level of the structure. For a given load arrangement the tubes existing at a distance from the plan's neutral axis will provide efficient resistance to bending, while the tubes existing at the neutral axis will undergo equal bending stress due to the rigidity of the tubular system. The core tube dwelling at the geometric centre offers larger resistance to bending and transverse shear from lateral load than the smaller peripheral tubes due to its extensive thickness and larger outer diameter.

To facilitate the ductile response of the structural system without inducing inelastic stresses in the tube, steel beams and trusses are placed between the tubes constituting a giant continuous spring-outrigger-truss, like a web diaphragm, that spans between the tubes in the vertical plane weaving them together. This is presented in Fig. 2(a). In addition the members constituting the web trusses are fully ductile enabling them to undergo plastic exertion at a fixed load dissipating energy and distributing forces to other ductile members going plastic in order. The formation of plastic hinges is hierarchical, beginning in the truss webs and proceeding to the external helical space frame encompassing the entire structural system, Fig. 3(a), which also acts plastically. Under the influence of large earthquake loads the helical space frame controls the structural response over elevation by adopting a large axial cross section that has an elastic axial load capacity larger than the design inelastic earthquake base shear force of the remaining structural system, minimizing lateral drift substantially. Fig. 3(a) presents this arrangement in a simple form.

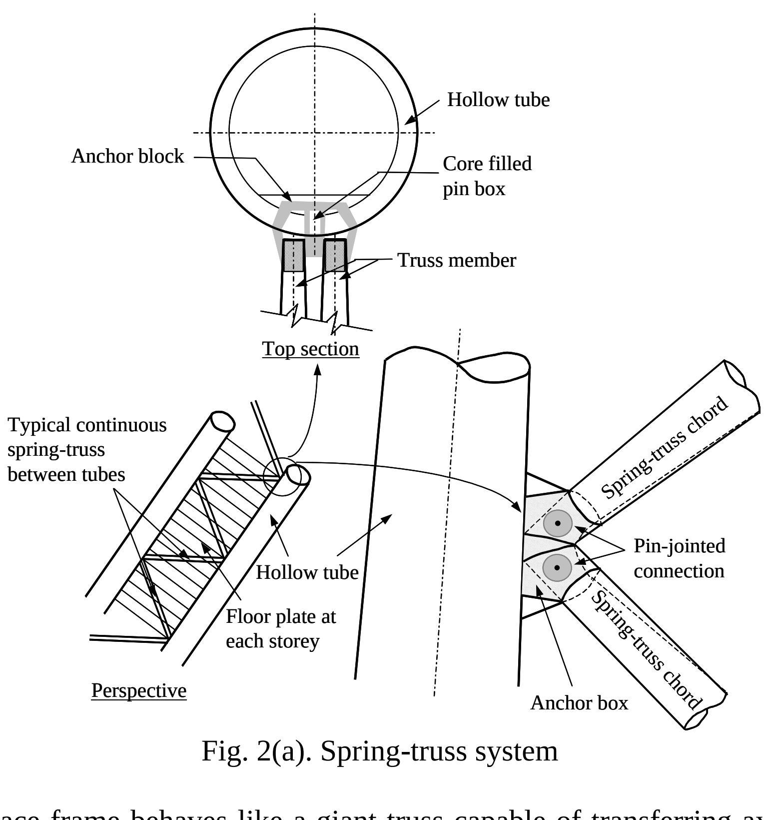


Fig. 2(a). Spring-truss system

The helical space frame behaves like a giant truss capable of transferring axial compression and tension only and connected at member ends by idealized pin joints unable to carry moments.

In this manner the helical truss undergoes inelastic deformation by controlled buckling in compression and ductile deformation in tension, reducing in axial area as the truss reaches higher elevations. In addition the taper present in the structural tubes and building elevation reduces the structure width at upper elevations to assist with vibration control and dissipation, effectively restraining the structural tubes and internal web trusses to act a single rigid unit in dynamic deformation. The inelastic behaviour of the structure is effectively provided by the truss web diaphragm and helical cage spanning between the tubes without compromising the stiffness which is purposely lumped into idealized controlled locations. The capacity of the tubes to resist bending in the elastic region is therefore increased and limited to elastic stresses at the onset of yield in the ductile systems weaving between them, to ensure that failure in the vertical gravity plane of the structure is prevented during an earthquake event (Hutchinson *et al.*, 1994). Furthermore, the base of the structure possesses the largest width and therefore also the largest axial areas of truss and helical cage analogously, to invert the earthquake vertical distribution of shear force as it would normally occur in structures of constant width over elevation.

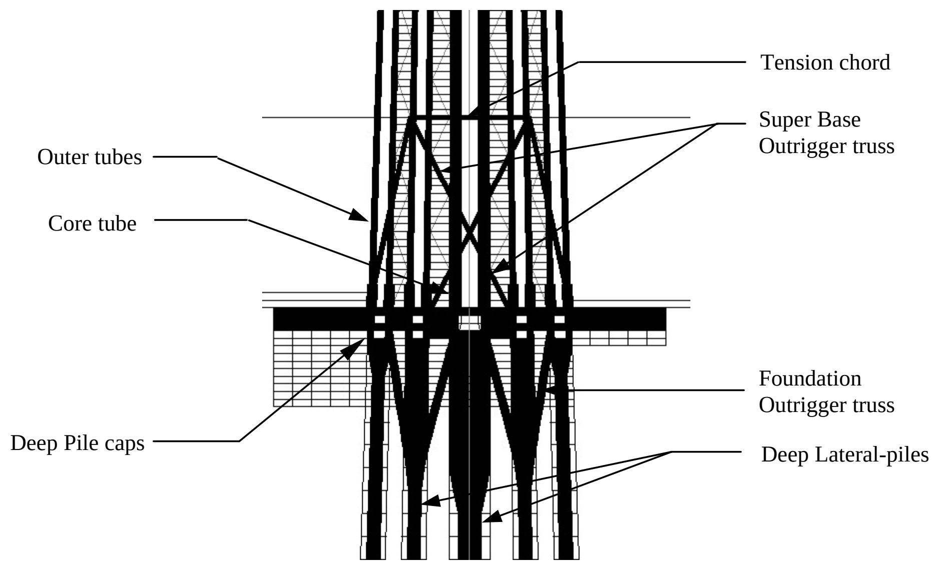
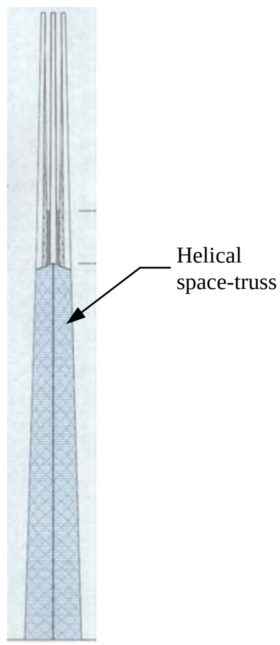
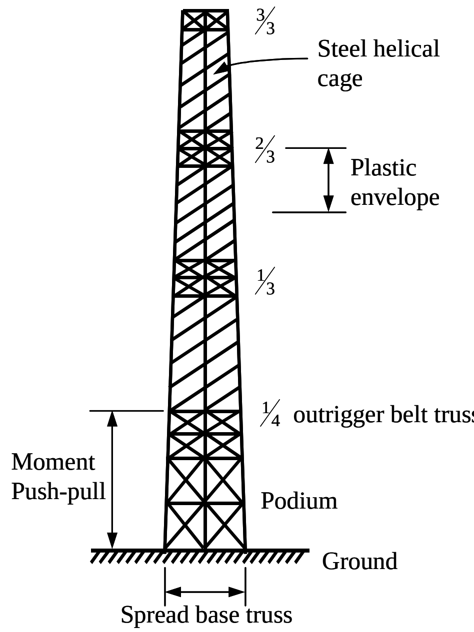


Fig. 2(b). Super base-outrigger truss

The structural base is also constrained by a super outrigger truss some 160m deep interconnected between the tubes and helical cage, as shown in Fig. 2(b). The effective purpose of the deep truss is to generate a larger base isolation capacity for the tubes at the lower storeys of the building, adding to the lateral stiffness of the system by inducing a stayed mast effect. The vertical displacement of the tubes in the first 30 storeys of the structure are controlled and dissipated by the super outrigger at the structures maximum dimension preventing the migration of shear forces in large magnitudes up the height of the building. Dividing the structure's height into thirds enables the lower third of the structure to be controlled axially (see Fig. 3(b)) and subsequently control the deflection of the upper thirds by an increased dimension at the base. The taper in the structural tubes also reduces their total dead mass further reducing the total axial stress at each cross section of the tube on every level of the building. Reducing the cross-section of the tubes over their height enables lateral loads to be transferred away from the upper levels of the structure into the stiffer and heavily damped structural base for dissipation (Soong and Dargush, 1997). The formation of plastic hinges can therefore readily be predetermined in proportion to a transient load at the maximum specified earthquake ground motion. The response of the structural system is orderly, forming hinges at upper regions of the base system progressing eventually to systems in the higher elevations, and controlled in deformation by the helical space frame at the periphery.



(a) Helical space frame



(b) Lateral stability system

Fig. 3. Helical space frame and outrigger trusses

Finally, the tubular arrangement behaves as a rigid dynamic system capable of withstanding large earthquakes while remaining stiff and controlled in lateral drift and purely elastic in the structural tubes. The base outrigger undergoes plastic deformation as part of the base isolation system transferring the stresses in the tubes to the helical cage at these levels within its elastic range, thereby increasing the plastic threshold of the entire structure. The multiple tubes are therefore kept elastic and free to move within the plastic systems so as to prevent damage to the structure's lumped stiffness during severe ground motions. The interaction of the internal web trusses provides an orthogonal outrigger effect at every storey of the building by dwelling in the interstices of the tube's grid parallel to the directions of load in both principal axes of the plan, as shown in Fig. 1. Combined with tighter spacing and larger axial areas at the structural base, the taper of the elevation and tubes enables the effective dissipation of vibration more efficiently and accurately within a reduced ductility demand for the whole structure. This in turn reduces the fundamental frequencies of vibration to below 0.2Hz and slows down vibration of the building. Therefore a natural response of the MHT system is to undergo excitation of higher modes of vibration, which distribute earthquake forces more evenly in proportion to the structure's taper over height. The resulting push-pull movement of the structure never reaches that of a pure cantilever and therefore the stresses and base shear of the structure are much lower than that experienced had the structure remained fully elastic in its fundamental mode of vibration.

The MHT concept effectively allows a more flexible structure to exist at higher slenderness ratios over larger elevations to contain adequate stiffness in the elastic domain and controlled deformation and stress patterns in the inelastic domain, mobilizing ideal tubular behaviour with larger spacing and façade areas than that of the framed tube system. The effective taper over height provides a natural aesthetic mechanism for the system to conform architecturally to the fundamental behaviour of the structural geometry and respond dynamically to massive inputs of earthquake energy without collapse or structural failure. Therefore the dissipative and flexible behaviour of super-tall buildings can be sustained and preserved efficiently utilizing the MHT technology.

THE DYNAMICAL DESIGN APPROACH

Seismic design of super-tall buildings

Super-tall building structures require accurate descriptions of structural response to transient and cyclic loads, due primarily to the extensive height and mass associated with their design. In addition the capacity of earthquake forces to excite higher modes of vibration at frequencies beyond the fundamental modes of vibration is critical, placing a higher demand on structural ductility and damping by distributing monotonic and hysteretic shear forces evenly over the structural elevation (Mazzolani *et al*., 1996). In particular the excitation and activation of inter-storey vibration at higher modes of frequency incur a larger percentage of base shear force at these levels beyond the magnitude of those outlined in earthquake codes. Combined with large mass, the ability of shear forces to migrate through super-tall structures governs the development and definition of elastic design stress limits and deflection limits respectively, particularly in view of the extensive tip deflection that may occur well beyond the limits of the individual storey.

The development of the MHT technology for super-tall structures requires an inelastic analysis to determine the elastic threshold at the specified design ground acceleration. The latter would constitute a codified response as outlined by the Eurocode EC2 (EC2 1991), but is based entirely on response spectra analysis and quasi-static earthquake base shear distributions acting in the fundamental mode of deformation. As such the initial determination of shear force distribution for the subject structure cannot be based on the fundamental mode of vibration, and an alternate means of accurately establishing the structures inelastic behavior under the influence of a shear distribution is required. It follows that the elastic threshold is established iteratively without concretizing the design elastic shear distribution during static pushover analysis, enabling the dynamic response of the structure to be examined under the influence of varying ground accelerations. This becomes critical once the structure reaches a plastic threshold effectively limiting the increase of earthquake base shear by redistributing increasing forces up the tower into elastic components. A higher envelope of shear force therefore reaches the structure’s roof, arousing the potential for in-elastic deformation in components not designed to behave plastically (Preistly, 2003). Justification for this philosophy comes directly from the nature of earthquake forces themselves, activating the vibration of structures by inertialy affecting their mass at the structural centroid, either plastically or elastically (Heart and Wong, 2000).

Transient seismic analysis

To establish the vertical distribution of base shear over the structure's height a method of dynamic analysis is mandatory, enabling the total sectional inertia and axial stiffness of each storey to be utilized in determining the effective distribution. To obtain the shear distribution for the subject structure a pseudo linear elastic time history analysis is carried out using STRAND7 (G+D Computing, 2003), and applied to a vertical lumped mass model comprising of a single stick column possessing the sectional properties of each floor. In addition the elastic stiffness of the stick is modeled at 50m lengths, requiring the total structure's mass to be lumped over 100-storey portions of the volume, and located at their respective centroid on the stick model. The shear force distribution resulting from the stick model can be normalized to the resulting base shear and distributed over the structural height as a fraction of the total base shear, set equal to a factor of 1.0. The magnitudes of the shear forces resulting from the pseudo analysis are irrelevant because they have been based on an initial assumed average value of storey stiffness in the lumped mass model. Following recent recommendations stipulated by the Structural Engineering Association of California and the associated Californian Earthquake Design Manual, the minimum design earthquake base shear a structure shall be subjected to is 2.5% of the total structural mass. The structural mass is assumed to be composed of the entire dead load and self weight and a partial sum of the live load, applied at the structure's base. Past and current engineering experience has shown that the total earthquake base shear for tall building structures can vary between 10 and 40 percent of the structure's permanent weight depending on the inelastic energy dissipation permitted for them in the deign codes for their respective regions (Fitzpatrick, 1992).

After establishing the minimum base shear applicable to the structure and its respective vertical distribution over the structures height, an elastic and inelastic analysis of the proposed structural system can be carried out. A 3-dimensional structural model of the building is developed to enable an elastic quasi-static pushover analysis to be carried out, which will be subjected to the base shear distributions beginning at 2.5% total mass. The allowable elastic stresses and deformations are determined as a function of the material strength and compared to the results yielded from the initial 2.5% analysis. Thereafter the base shear is increased by 0.5% intervals of the structural mass until the elastic limit is reached, which is defined as the maximum elastic base shear that the super-tall building can withstand. Further an inelastic pushover analysis of the same structural model can be carried out at increments of 0.5% mass analogous to the elastic pushover analysis, until maximum elastic stresses are reached in the column elements and the maximum allowable ductility ratio is obtained in yielding elements between the columns. The plastic exertion capacity of the structure can therefore be measured at a total maximum value and envelop the cyclic plastic loading occurring in actual transient events. The latter postulates that the cyclic loading of the structure occurs at plastic load magnitudes equal to or below the design ductility ratio of the structural system, determined from the elasto-plastic force curves of the pushover analysis. The resulting elastic stiffness of each storey in the structural model can be determined by measuring the slope of the elastic region in the elasto-plastic curves, and assigned as a synthetic modulus of elasticity for each storey in the lumped mass model. The plastic hinge formation in the pushover model is achieved by incorporating fuse members within the structural system that are capable of sustaining a maximum elastic force at the prescribed maximum elastic base shear and thereafter remain fixed at the elastic force without increasing in magnitude, except for continued plastic deformation. The compatibility forces are applied as reverse forces in STRAND7 preventing the redistribution of moments and shears into the tube columns, instead activating the plastic deformation of unstressed remaining fuse members spanning between the tubes.

In addition to the shear force elasto-plastic behavior, the moment-rotation behavior of the joints between spring-trusses and web diaphragms to the vertical tubes is modeled and estimated using monotonic initial loads to develop moment-rotation elasto-plastic curves. These are set up in proportion to the elastic capacity of the tubes, allowing the distribution of forces to be directed along the continuous spring trusses that act as a web diaphragm between the tubes in the upper stories of the structure and down toward the increasing structural base. The taper over the elevation is consequently tested and utilized in proportioning to the tube's dimensions depending on how much force is limited by the angle and extent of the taper. In addition the rotation capacity of joints between the web trusses and the tubes can be isolated and a stiffness predetermined by adopting the natural load paths that form in the new tapering geometry as a function of the lever arm between the truss chords and the floor spans. In this manner the dynamical response of initial tubular proportions can be optimized easily before a detailed finite element analysis is required. This in turn ensures that the global response of the structure is well understood as a function of the gravity design as preliminary architectural dimensions are decided.

<u>The dynamical design procedure</u>

Examining the function of the hollow-tubes within the MHT concept reveals the potential stiffness of the system when distributed around the peripheral zone of structural floor plans at a lever arm distance producing a moment couple greater than the largest design earthquake overturning moment. Therefore this requires proportioning the hollow-tubes wall thickness and outer diameter in relation to the tapering mass and geometry of the structure and in proportion to the maximum vertical stress. It follows then that the thickest and thinnest dimensions of the tubes match the curtailing mass and geometry of the structure, automatically enabling a uniform maximum structural stiffness to remain continuous over the full height of the hollow-tubes. The tubular profile in elevation of each hollow-tube therefore matches and defines the structure's overall mass and form with an optimized elastic and plastic capacity for seismic shear force control. Further, predetermining these mass and stiffness values as a function of the structural base increases the lateral capacity of the system by limiting the mass and lowering the frequency of the upper stories of the structure.

Two fundamental design parameters are critical to designing the hollow-tubes and the web trusses between them. These are the moment-rotation capacity of each tube and the shear force-deflection capacity of the web truss-hollow-tube arrangement. It follows that as forces are redirected to the structural base outrigger, shear and moment forces will dissipate away from the upper levels of the structure and migrate downward toward the stiffer base and vibrate about the lower centre of mass. Therefore, structural design revolves around iterating the taper of the structure and the hollow-tubes towards optimum slenderness and maximum thickness at the base of each tube. Defining and determining the moment and shear stiffness of each tube and then the tubes all as a single system enables the gravity design to be re-proportioned by redirecting the vertical (mass) loads as a function of their slender taper. This approach determines the thickness and diameter of the tubes laterally as a function of both the vertical mass and its ability to vibrate at various depths of tubular cross-section. It follows that gravity design directly influences seismic design, and therefore the dynamical design approach quantifies this effect on the lateral forces and therefore the physical dimensions of the tubes.

The dynamical approach utilizes two iterative global analysis stages and two detailed final FEA design stages to optimize the tubular dimensions and the structural taper. Within the first 2 iterative analysis stages, 2D plane models and lumped mass/stiffness models of 2 DOF are developed and used to iterate the global response and proportioning of the hollow-tubes. The first iteration stage incorporates linear and nonlinear pushover analysis to estimate the moment-rotation and shear-storey drift capacities of the tubes. In addition a pseudo time-history analysis is carried out to determine the proportions of mass and slenderness required as the tube's cross-section is designed. The time-history model adjusts the percentage of shear force migrating throughout the structure as the slenderness is adjusted to dissipate it. In addition, the mass is curtailed at each ascending storey until an optimum balance is obtained. The second iteration stage refines the models used in the first stage, and employs real design seismic ground-histories over a full mass model of every storey. Two degrees of freedom are analyzed in this stage rather than separately as in the first stage, to examine their effects on a much more accurate mass and stiffness model. The tube dimensions and sections are further refined in proportion to both gravity loads and lateral loads as the magnitudes of earthquake base shear force converge to a common percentage of the buildings mass. An inelastic nonlinear time-history analysis is used as the primary design tool after elastic thresholds have been fully developed in the structural base and spring-truss elements.

The final two FEA design stages incorporate a coarse-mesh global model of the hollow-tube system subjected to storey shears derived from the elastic and inelastic time-history analyses. Both elastic and inelastic forces are used to test the tube's capacity for penetrations and openings not accounted for in the first iterative stages of the design. Local rather than global refinements can therefore be made without drastic redesign. Further, sub-modeling of individual components, such as the hysteretic behavior of beam-column joints, can be done at a reduced scale with finer meshes considering the global boundary conditions derived from the inelastic time-history analysis. Therefore the design approach is thoroughly dynamical enabling all components and joints to be designed as a function of the global response of the structure rather than discrete separate elements maintaining no reference to the continuous stiffness and flexibility of the MHT system.

CONCLUSION

The dynamical design approach based on the Multiple Hollow-Tube concept (MHT) for the design and development of super-tall slender buildings is presented in this paper. The helical spring-truss and super base outrigger truss systems are proposed for a subject super-tall building with an aspect ratio 12:1. The development rationale is discussed in some detail.

The numerical verification of the proposed dynamical approach to structural design and development of the subject building is presented in the companion paper (Gustafson *et al.* 2004).

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