The Third International Conference on
Advances in Structural Engineering and Mechanics
Seoul, Korea, September 2-4, 2004

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

A.K. Gustafson[*1)], J.W. Langer[2)], and H. Guan[3)]

[1), 2)] *Robert Bird + Partners International consulting Engineers, PO Box 7035, Riverside Centre, Queensland 4001, Australia*
[3)] *School of Engineering, Griffith University Gold Coast Campus PMB 50 Gold Coast Mail Centre, Queensland 9726, Australia*
[1)] *agustafson@robertbird.com.au*

ABSTRACT

Based on the Multiple Hollow-Tube (MHT) concept and the dynamical design approach, as outlined in the first paper of this two-paper series, the numerical verification of the subject super-tall building with an aspect ratio 12:1 is presented in this paper. The theoretical seismic response of the building is analysed in some detail. The applicability and effectiveness of the proposed dynamical approach in the design of super-tall slender buildings is also examined.

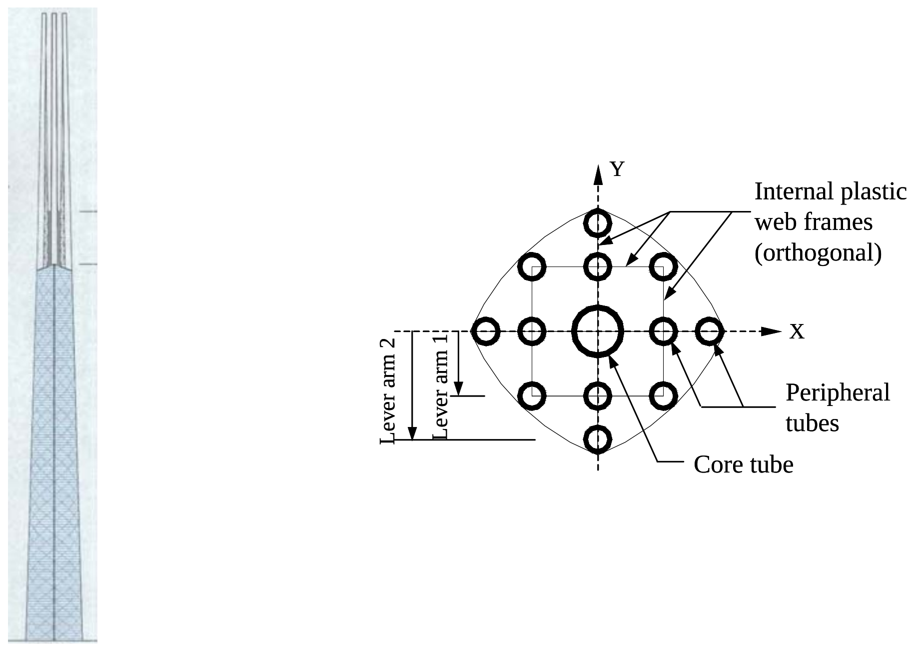
INTRODUCTION

The MHT concept as discussed in the companion paper (Gustafson *et al*., 2004), has been applied to a subject structure of slenderness ratio 12:1, with tapering geometry and curtailing mass as presented in Fig. 1. The tubular layout has been chosen such that the model for numerical analysis is symmetrical and orthogonal in set out, assisting the simplicity of the verification process. The dynamical design procedure outlined in the companion paper has been adopted to carry out an analysis and design on the subject super-tall building and results summarized to substantiate the theoretical development of the MHT system for such buildings. A series of linear and nonlinear time-history analyses have been carried out to determine the effectiveness of the spring-truss system and the helical space-truss for plastic exertion, and the applicability of such systems to structures of all geometries examined within the context of these analyses.

Hence, the layout and distribution of stiffness inherent in the MHT concept is demonstrated

[1)] Structural Engineer
[2)] Structural Engineer
[3)] Senior Lecturer

using dynamic analysis as a design tool for proportioning and exploiting slenderness and extensive height in structures that would otherwise be overlooked by typical standards of practice. Finally, the applicability of dynamics to structural design is considered as a consequence of the parameters utilized in the time-history analyses, and related back to the benefits of curtailing mass and increasing stiffness in discretized lever arms about the spreading structural base.



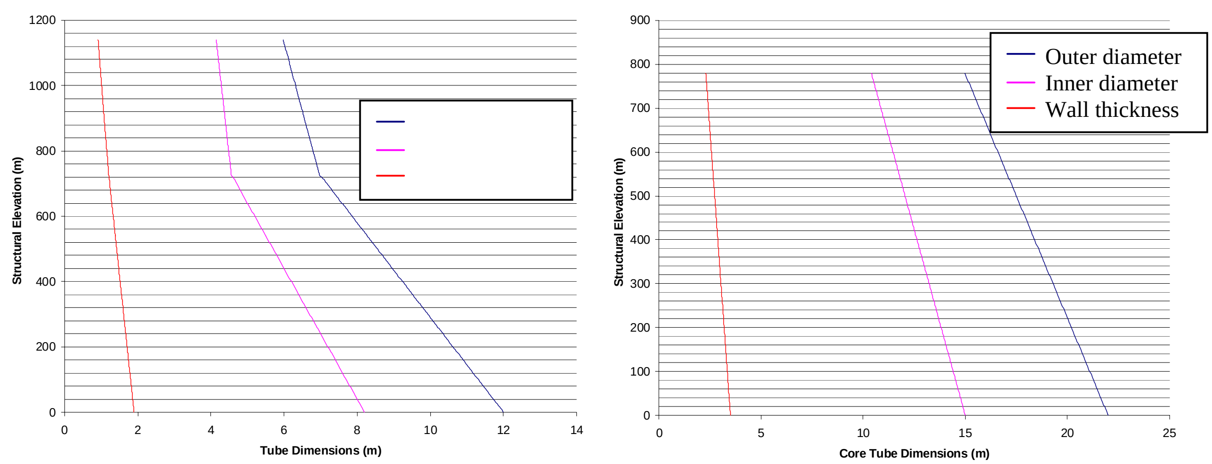
(a) Elevation (b) Footprint and tube layout

Fig. 1. Super-tall building

THEORETICAL SEISMIC RESPONSE

To establish the effectiveness and capacity of the MHT concept, a slender super-tall building of 1000m height as shown in Fig. 1, has been adopted specifically to identify the migration patterns of earthquake base shear up the structure's height. A Finite Element Analysis System STRAND7 (G+D Computing, 2003) has been used to carry out the analysis. In addition the resulting iterative elastic maximum static earthquake loads derived from time-history analyses as a function of the optimum hollow-tube dimensions were established to present the effect tapering slenderness and mass have on the motion of tall structures, as optimum curtailing mass to tube-slope are approached. From these global analyses the dimensions and required properties of the spring-truss system were established and identified as the design iterations eventually produced controlled and inverted patterns of base shear 'build-up'. Hence, the predetermined and ideal locations of plastic-hinge formation within these trusses were identified and used to modify the elasto-plastic curves for ductility, which also in turn modifies the time-history response of the structure. It follows that the analysis iterations would lead to a fixed ratio of tube-diameter to tube-thickness for a given level of plastic behaviour that would remain fixed as a structural design ratio. A subsequent target displacement for elastic and inelastic response is thereafter established by iterating the sectional dimensions required for the helical space truss, controlling the base shear migration even further, and subsequently modifying the elasto-plastic curves for greater levels of ductility or added manufactured damping. The levels of natural and manufactured damping were then established in relation to the stiffness and acceleration behaviour of the super-base structure and the upper storeys.

The optimum tube dimensions were established over the structural height as a function of the gravity loads acting on the tubular cross-sections via a floor tributary area. The cumulative stresses for a given thickness to outer diameter were tested and modified until less than 50% of the tube's axial capacity was absorbed by these gravity loads. Tube shape functions were established for two regions over the structure's height and described mathematically for application to lateral analysis. Figs. 2(a) and 2(b) present the shape functions over height for the peripheral and core tubes respectively, depicting the abrupt increase in outer diameter at 750m elevation. The change in slope of the function has been established to stiffen the upper storeys of the structure purposely to match the height at which the core tube terminates. The resulting cumulative axial stresses for the peripheral and core tubes are presented in Fig. 3. It can be observed that the cumulative axial stress in the tubes is near 40% only at the structural base, thereafter the capacity absorbed reduces dramatically past 150m elevation, which reflects the optimum tube functions inducing thicker heavy tubes at the base and relatively thinner lighter tubes at higher elevations.

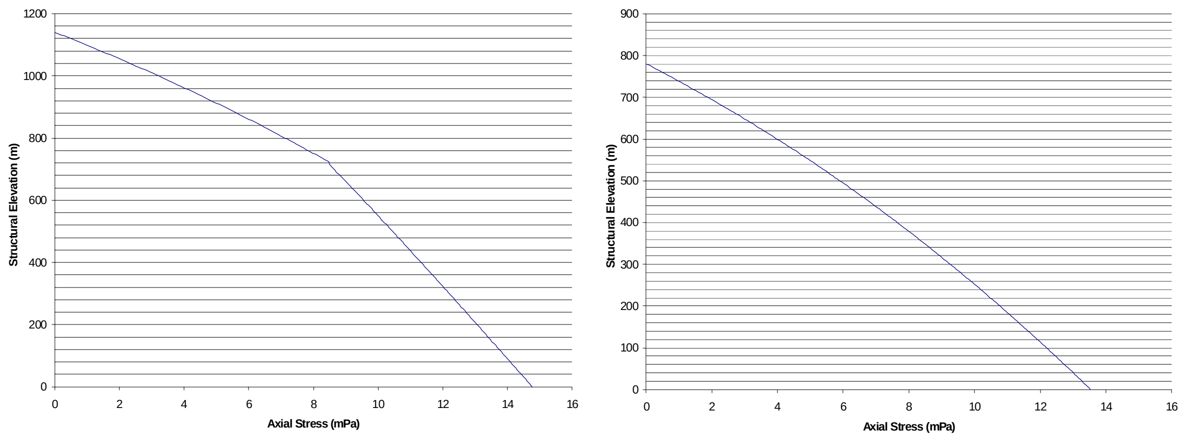


(a) Peripheral tube dimensions

(b) Core tube dimensions

Fig. 2. Optimum hollow-tube dimensions

The 'bell-bottom' effect is achieved in the tubes which enables the relative thickness and outer diameter of the tubes to be increased without exceeding the axial capacity of the base cross-sections. This is observable in Fig. 2(a) between the slopes of the outer diameter and the tubular thickness profiles. All iterative design remains fixed about these profiles and the confinement ratio defined by the 'bell-bottom' of the tube's base section.



(a) Peripheral tube axial stress (b) Core tube axial stress

Fig. 3. Cumulative tube axial stress

The lateral stability of the tubular layout presented in Fig. 1(b) is therefore dependent on the unused reserve capacity of the tubular profiles, and therefore the dimensions and thickness of the tubes determined from gravity design. The ideal moment of inertia was established for each storey as a function of the gravity design, such that the mass and tapper of the tubes at optimum gravity load case also yielded the greatest magnitudes of moment of inertia about each storey. In addition the continuous stiffness profile of the tube dimensions themselves automatically ensures a smooth continuous moment of inertia profile over structural height without any abrupt kinks of drops in stiffness. By iterating between the curtailing mass at each successively higher storey and the bending stiffness required there, the optimum tube shape functions begin to reflect the dynamic relationship between lateral and axial vertical loads. Using the tube dimensions shown, the optimum inertia profile versus structural height for the building in Fig. 1(a) was established mathematically, assuming that the tubes would remain uniform in bending due to the action of the helical space-truss. This profile is presented in Fig. 4.

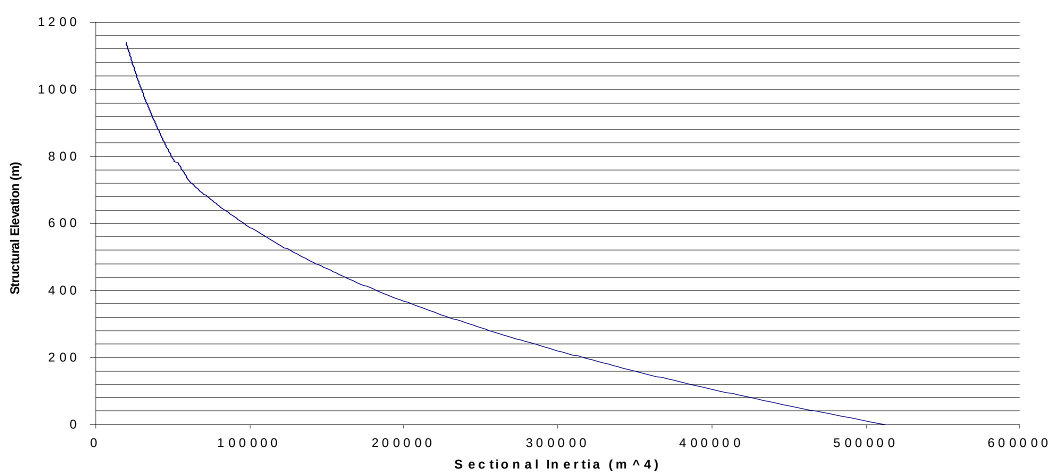


Fig. 4. Moment of inertia profile about X &Y-axes

The inertia profile exhibits the same rapid increases and decreases in slope as reflected in the optimum tube profiles in Figs. 2 and 3, corresponding to the 'bell-bottom' effect adopted to manage the stress capacities. It is evident that curtailing the mass in the upper levels to a point where the containing lateral stiffness is significantly larger, but less than the level preceding it, leads to an inverted migration pattern of earthquake shear force. Therefore designing the helical space-truss or spring-truss system becomes substantially easier and remains an exercise of deflection control by proportioning axial stiffness.

A structural stiffness model was defined based on these properties and subjected to several monotonic load patterns based on the static equivalents for a total earthquake base shear force of 2.5% structure mass. From these analyses the elastic stiffness of each storey or lumped segment was obtained and iterated to reflect the worst-case load distribution. These elastic profiles were then used to run an initial elastic time-history analysis on a stick model to determine the shear force migration patterns based on mass and elastic stiffness. Thereafter modifications to the elastic stiffness were made in proportion to the inertial loads derived from the time-history analysis, and reapplied to the structural models until an optimum shear force migration pattern was achieved. Deflection limits for global response and inter-storey response were used to establish the maximum rotation and displacement forces within the spring and helical truss systems after their effects on the elasto-plastic curves were incorporated into the stick models. Inter-storey drift limits were set at 1:200 and 1:100 for a peak ground acceleration of 0.25g and 0.5g, respectively. In addition the ductility ratio limit was set at a maximum of 3 past the elastic limit of the helical space-truss during plastic exertion. After several interaction cycles between static and dynamic analysis the optimum elastic structural stiffness versus structural height was established as shown in Fig. 5, and utilised for time-history analysis adopting several earthquake ground histories of moderate to severe intensities.

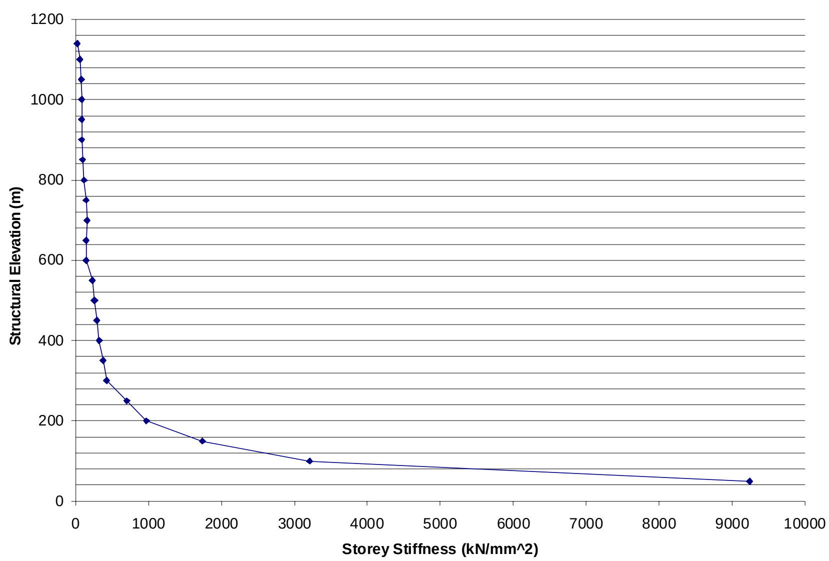


Fig. 5. Elastic structural stiffness over height

The resulting earthquake base shear distributions over the structural height was established, as presented in Fig. 6, using an envelope encompassing the worst case ground acceleration response time-history in the elastic and plastic ranges, respectively. The response of the optimised system was measured against three varying earthquake records and referenced to the elasto-plastic curves defining the properties of the structure as it moves in and out of nonlinear deformation. The elastic range of earthquake base shear was found to be 5% of the structure's total similarly the plastic limit if earthquake base shear was some 9% of the structure's total mass. Fig. 6 portrays the migration pattern of base shear as a percentage of the structure's total mass in relation to the maximum migration envelope from dynamic analysis depicted in the inset graph above it. It is evident that the base shear has been redirected to the structural base where the largest magnitudes of stiffness and spreading moment reside, suggesting that the curtailed mass and increased stiffness inherent in the structural taper have inverted the shear force migration pattern that would otherwise build up greater intensities in upper storeys. In addition the dynamic shear force distribution, regardless of its percentage of migration at upper levels, has been controlled and dissipated to the base of the structure, presenting an almost static structural response. The dynamic shear force distributions shown are maximum shear force values for each storey out of the full time record of the respective earthquake time-history, and therefore depict the worst case series of base shear forces. Intermediate points of base shear migration are similar in profile, distribution and much less in magnitude.

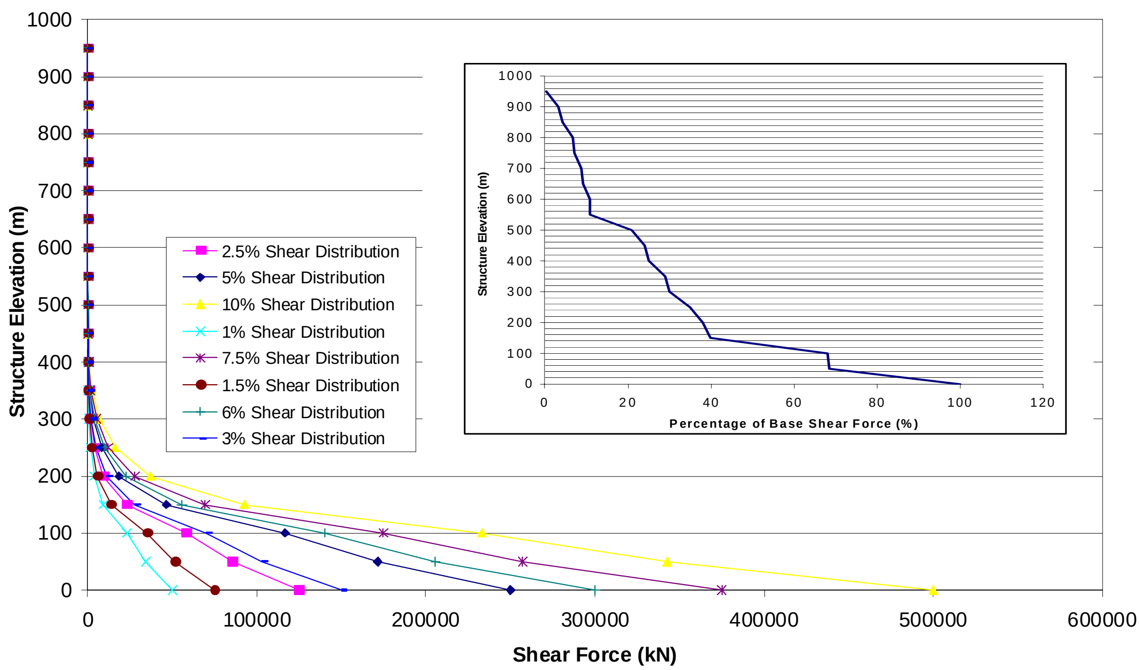


Fig. 6. Maximum static and dynamic earthquake base shear migration patterns

Maximum lateral deflections were observed to be within the allowable inter-storey drift limits for both the elastic and inelastic ranges, with an expected peak lateral drift corresponding to the shear force migration patterns presented in Fig. 6. This demonstrates that the spreading base lever arm has effectively lowered the static earthquake couple of the structure by curtailing the structural mass with progressive height. Further the slenderness profile of the tubes induce a corresponding shift and transfer of earthquake shear that migrates down instead of up, controlled by the continuous stiffness of the tubes, the spring-truss, and the helical space-truss confining all of them. It is expected that the deflection patterns would reach a maximum at the structure's tip or at half height relative to the ground. However, the observed inter-storey drift occurs at the location of shear force transfer where the inflection of relative floor velocities is at a maximum, as shown in Fig. 7, and therefore an ideal location for manufactured viscous dampers. The dissipation of vibration by the tapering system is significant, inducing slower frequencies of fundamental vibration in the upper structure and relatively higher frequencies of vibration at the structural base. The fundamental frequency of vibration for the subject structure was found to be 0.1Hz, which is consistent with the shear force migration patterns observed in the time-history analyses.

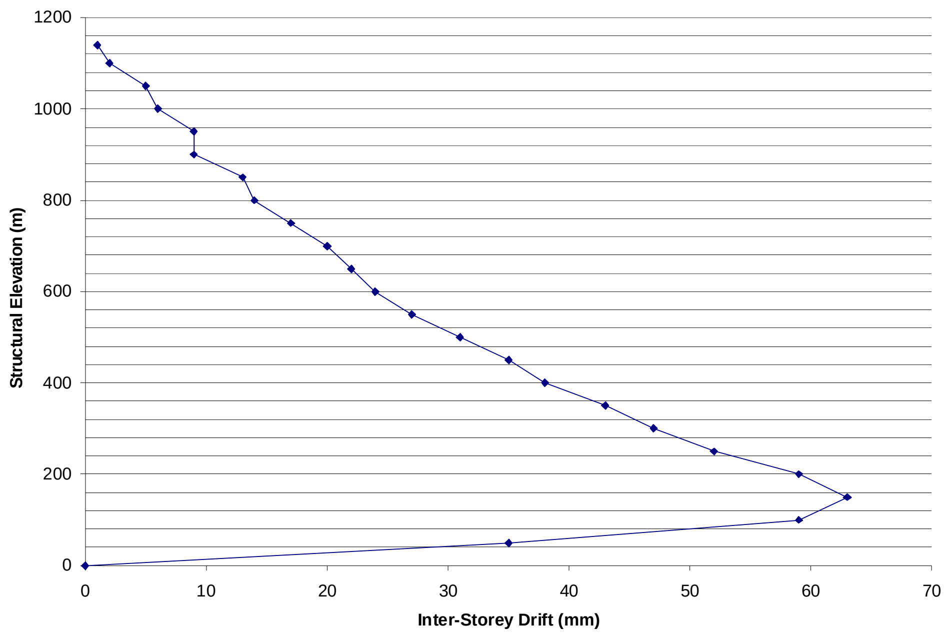


Fig. 7. Maximum inter-storey drift

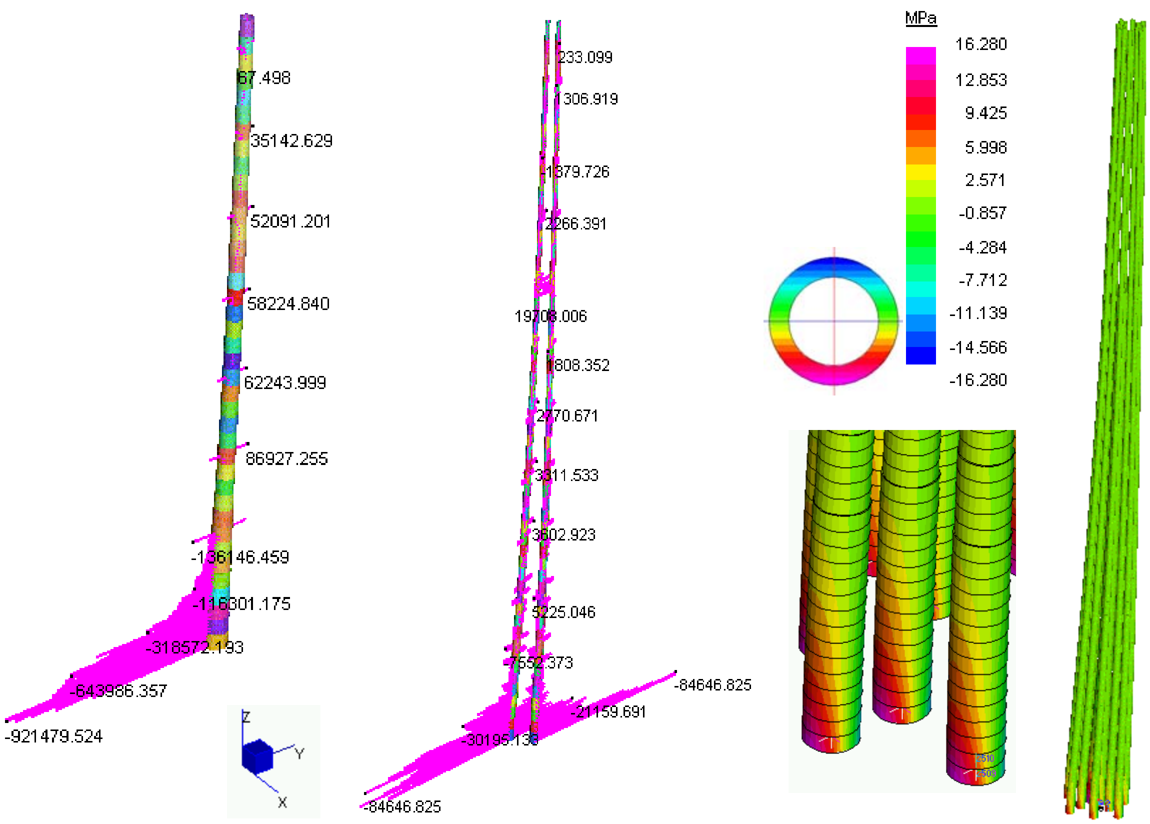
The 3-Dimensional model adopted for the linear elastic quasi-static pushover analysis is now re-examined with increasing loads in the inelastic region of material stress, based on the plastic deformation designed into the helical space frame, super outriggers, and truss web diaphragms. The initial member dimensions adopted for the tubes and steel elements in the static design are used in the first increment of nonlinear load, and thereafter redesigned to permit the allowable maximum plastic load to be developed without incurring plastic stresses in the concrete tubes above 100m in elevation. In addition the super outrigger persisting at the structure's base is redesigned in cross section to achieve the required dissipation at the inelastic maximum load and control the exertion of the lower soft storey. Cut-off loads for the ductile members are established from the nonlinear analysis based on the maximum determined inelastic base shear distribution in Fig. 7, and the required ductile capacity within the structural base. The determined elastic stiffness for each 50m segment of the linear elastic structural model at 3% base shear, as presented in Fig. 6, is re-examined within the new proportions developed by inelastic design at the determined maximum design base shear. The effective material stress yielded form inelastic analyses at 5% base shear are elastic in nature, and provide an accurate description of the storey stiffness over height at larger tube proportions. The resulting storey stiffness distribution is therefore larger than the distribution determined at linear elastic pushover loads and accounts for the inelastic yielding and damping predominant in the structural base.

From the nonlinear quasi-static pushover analysis it was established that a maximum base shear distribution pattern of 9% structural mass can be withstood by the structure ensuring stresses in the tube are below elastic limits beyond 100m elevation. The cut-off loads for the truss web diaphragm members has been established at 34,000kN tension and compression over the structure's entire height, directly in response to the maximum elastic load that the cross sections of these members can withstand. In addition the helical space frame encapsulating the structural tubes has been divided into two separate cut-off regions, beginning at base level and again at 100m elevation at the termination of the super outriggers. The taper of the structure induces a distribution of stress that decreases in magnitude as the structure deforms plastically, reducing the required plastic load at higher elevations by 10% of the base helical frame. Subsequent ductile cut-off loads for the helical cage have been set at 300,000kN at base level and 180,000kN at 180m elevation, and finally at 95,000kN at 400m elevation up to the structural remaining height. Figs. 8 and 9 present the resulting total bending stress in the tubes from the elastic to inelastic region, depicting the optimum stress response of the MHT system under seismic loads. It is evident that the structural base absorbs a majority of the seismic load while inhibiting the base shear force from migrating up the structure. As plastic dissipation and nonlinear damping occur in the structural base, excitation of the upper levels of the structure becomes exceedingly more difficult, redirecting any smaller forces back into the structural base. The maximum elastic bending stress at the peripheral tubes base was found to be 16MPa at an earthquake base shear equivalent to 250,000kN. The maximum inelastic bending stress at the peripheral tubes was found to be 21MPa at an earthquake base shear equivalent to 500,000kN.

CONCLUSION

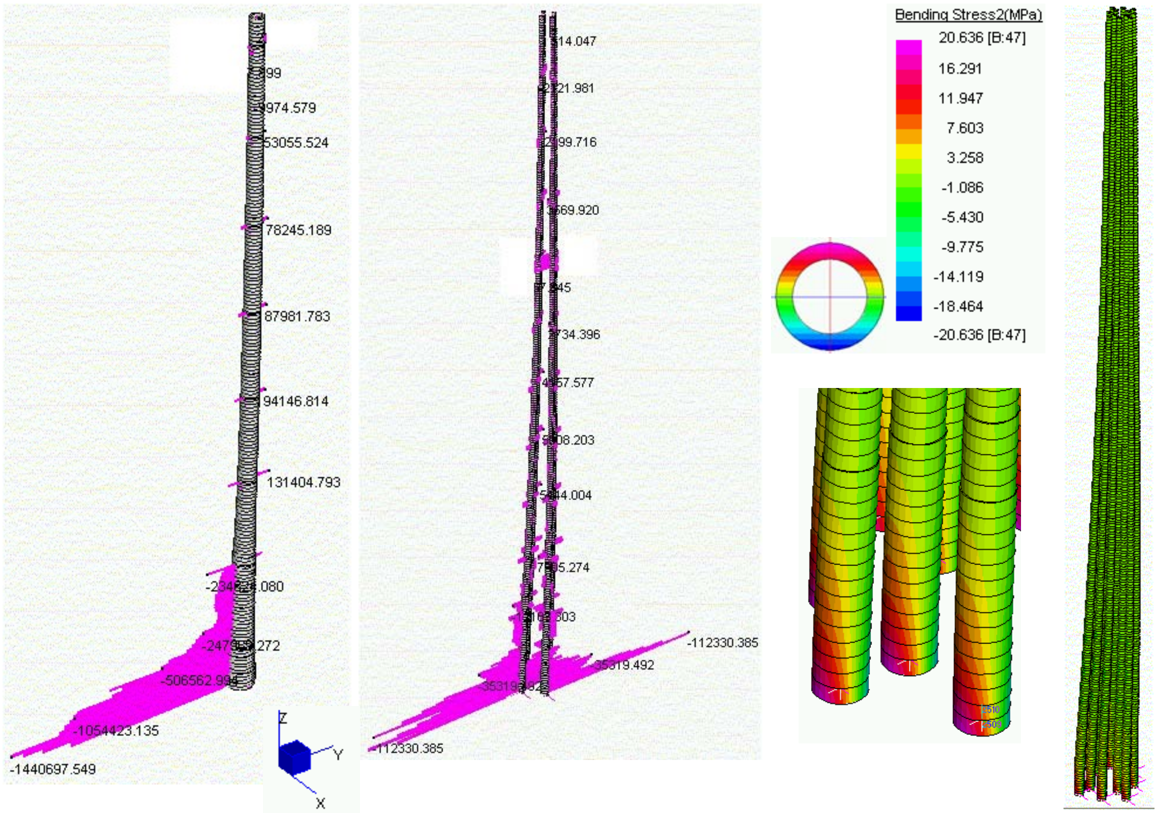
Considering the results presented, particularly the linear elastic and nonlinear inelastic time-history shear force distributions in Fig. 6, the performance and behaviour of the structural system under seismic load is optimal. The development of inelastic yield and deformation at locations predetermined for structural hinge formation are optimal and controlled hierarchically by the addition of the helical space truss encompassing the entire tubular system. The dissipation capacity of the system at the structural base is significantly aided by the taper present in the structure and corresponding tubes over the elevation, lowering the frequencies of fundamental vibration substantially enough to cause slower vibration of the structure under seismic events. The plastic yield developing over the first 15 storeys of the structure base enables the super outrigger system to maintain the elastic integrity of the tubes over the remaining height of the structure, reducing the total lateral drift significantly. In addition the plastic hinges developed in the lower storeys of the tubes are effectively capable of dissipating input energy at some 30% of critical damping.

The elastic response of the tubes under the influence of base shear values equal to 20% of the total structural mass ensures the structural integrity of the building during maximum credible events, effectively raising the stiffness of the structure in the elastic domain. Further, the development of plastic hinges in the helical space truss ensures that the onset of yield is controlled in an ideal order, yielding the migration of shear forces up the structure to invert, and migrate to a maximum in the structural plastic base. This is further aided by the hierarchical formation of plastic yield over the structural taper, causing the upper levels of ductility to constrict the development of massive shear force from entering the upper mass of the building. Consequently the remaining elastic strength of the tubes beyond 160m elevation above ground level is available for resisting wind loads within the elastic region also. The distribution of shear force over the structure's height is controlled, as evidenced in Figs. 8 and 9, by the large axial area present in the members constituting the helical space truss, providing an increased lateral stiffness that enables deformation from seismic input to be absorbed elastically in the upper regions of the structure and inelasticity dissipated in lower regions of the structure. This effect is analogous to the concept of rapid nonlinear damping, in which higher velocities impart smaller forces unto the structure during threshold base shear forces.



(a) Core tube shear force (b) Peripheral tube shear force (c) Total bending stresses

Fig. 8. Hollow-Tube bending stresses (maximum linear earthquake base shear case)



(a) Core tube shear force (b) Peripheral tube shear force (c) Total bending stresses

Fig. 9. Hollow-Tube bending stresses (maximum nonlinear earthquake base shear case)

Ascertaining the optimum ratio of stiffness to mass and flexibility is paramount in dynamic design, affecting the entire structural design process by first reducing or increasing the resulting seismic loads. Further, the continuous distribution of stiffness provided by the flexible spring-truss and plastic helical space-truss affect the manner in which storey masses are activated by ground accelerations, redirecting and inhibiting the build-up of shear force past certain structural heights. It is evident from Fig. 9 that the base shear is concentrated exclusively in the structural base system, where restricting lower levels of stiffness in the upper storeys past the base prevent the shear from climbing vertically. In existing structures typical shear migration is induced by developing the full plastic capacity of the structure's base, and therefore spreading upward throughout the remaining elastic storeys of the structure, enabling significant percentages of the maximum base shear to reach the structure's roof. However, the results provided in this study demonstrate that the elevational taper coupled with the nonlinear stiffness effects of the helical truss and spring-truss, induce a cap unto this tendency proportional to the centre of gravity of the tube system, preventing the plastic base shear from migrating up the structure's height. It was observed that linearly increasing magnitudes of earthquake base shear are controlled axially by the flexibility of the truss joints and reduced to an intensity that matches the damping capacity of the super base-outrigger system. Therefore, curtailing the mass and increasing deformation stiffness over height limits the distribution of shear force transferred to the vertical tube elements, ensuring they remain purely elastic. The common diagonal alignment of members in the helical truss is typical for all trusses, but when combined in three dimensional space, the strut and tie action is much more capable of restraining and absorbing lateral loads, and therefore suggests that the buckling capacity of the constituent members relative to their length (which decreases with the decrease in structural width over height) is an ideal mechanism for ‘plastic exertion’.

The flexibility of the truss and the MHT system means that its application to structures of any geometry and height is ubiquitous. By exploiting salient features of slenderness and curtailing mass within the structural design, the dynamical approach can be applied to yield an ideal arrangement of tube geometry that reflects and manifests the desired behaviour reflected in this study. Further, the continuous distribution of stiffness and flexibility provided by axially acting members is critical to the effective application of the concept, suggesting that a new percept of flexibility to stiffness design employs traditional truss techniques with untraditional applications to deflection control and plastic exertion. Therefore the dynamical approach to design is initiated architecturally and structurally to bring about optimization.

Given the results presented and those theoretical assumptions associated with the design and modelling procedure, the feasibility of designing and developing super-tall buildings in light of the qualitative force patterns observed in the time-history analyses is substantially realistic. The capacity for super-tall buildings to sustain large earthquake forces using an MHT arrangement is immense. Optimal arrangements of multiple tubes and ductile axial elements, such as the helical space-truss developed in this study, are enabled to exist at higher elastic thresholds than structures of a lesser elevation. In addition the capacity of the Multiple Hollow-Tube structural system to provide adequate levels of stiffness and vibration control behaviour is excellent and ideally suited to highly flexible slender structures at extreme elevations. Therefore the MHT concept can be used to construct super-tall buildings efficiently under the influence of transient and seismic loads. The results obtained in this study suggest and warrant the development of further research to refine the proposed tube system into other more complex curvilinear geometries, for a broader behavioural verification.

ACKNOWLEDGEMENTS

The support from the 2004 Griffith University Research Grant is gratefully acknowledged.

REFERENCES

Gustafson, A.K., Langer, J.W. and Guan, H. (2004), “A Dynamical Approach to Structural Design and Development of Super-Tall Slender Buildings Based on Multiple Hollow-Tube Concept: Part I Theoretical Development”, *Proceedings of the 3rd International Conference on Advances in Structural Engineering and Mechanics (ASEM’04)*, Seoul, Korea, 12p.

G+D Computing (2003), *STRAND7 User Guide and Reference Manual*, Sydney, Australia.