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THE EFFECTS OF COMPLEX GEOMETRY ON TALL TOWERS

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SUMMARY

Advancements in the application of computational capabilities to the design and analysis of building structures has enabled the realization of tall buildings with complex geometries. This paper explores some of the design issues and tools used to achieve cost effective solutions for tall, tapering, twisting, or leaning towers. Copyright © 2007 John Wiley & Sons, Ltd.

1. INTRODUCTION

Modern design and analysis tools are giving architects and engineers the opportunity to design buildings in shapes and forms never before imagined for tall buildings. All around the world, new and unusual tall buildings are being announced that will stretch the abilities of both their designers and the contractors that will build them.

This paper explores some of the particular challenges and opportunities that are created by towers that have unique geometries or articulated forms, and discusses some of the design and construction techniques that can be used to make these unusual buildings more economic.

2. PLANNING CONSIDERATIONS

The most fundamental challenge to the design team for non-prismatic towers is how to deal with the shifting floor plate. Through skillful design, any programmatic inefficiency created by the variation in floor plates should be offset by the added value that the uniqueness in the form and layouts brings.

Mixed-use towers have a planning logic that can often lead to unusual shapes. Elsewhere program areas for tall towers tend to be repetitive, and in some instances a vertically extruded shape provides the most efficient volume for the required program.

In towers where floorplates twist, lean, or taper, each floor is often unique. The key to making these buildings work lies in the architect's ability to arrange the program in such a way as to deliver repetition and consistency for the program elements that need it, and use up the remaining variable space with more flexible program blocks where the additional but inconsistent space can at best add value or at worst minimally impair the desired functionality of the space.

A typical example to display this point is a tapering apartment tower. Bedrooms and living rooms are more flexible spaces and are generally most desirable to locate on the perimeter for views. Kitchens and bathrooms are less flexible. It is preferable to stack kitchen and bathrooms vertically, and let the living areas and bedrooms morph to accommodate the building shape changes as far as practical, only offsetting risers as infrequently as possible. The challenge with articulated office towers is to

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Figure 1. Twisted, tapered, tilting towers. From left to right: Songdo Northeast Asia Trade Tower (Kohn Pedersen Fox); Milan Fiera (Studio Daniel Libeskind); and Al Raha Beach Residential Tower (Asymptote)

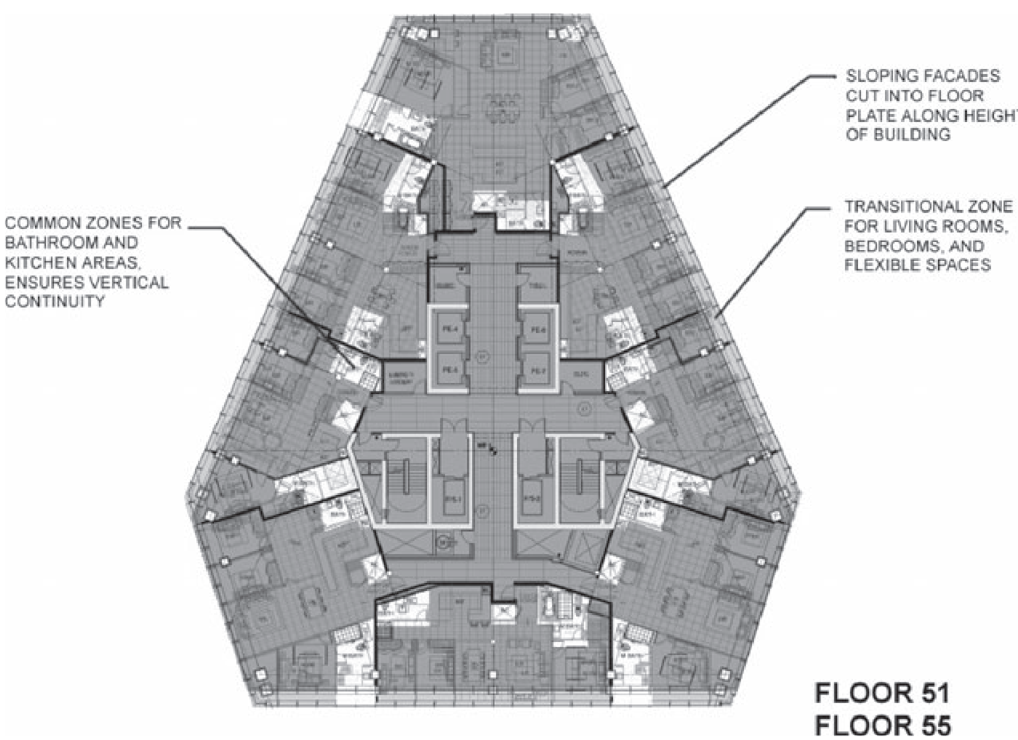

Figure 2. Songdo Northeast Asia Trade Tower floors 51 and 55 apartment planning zones

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maintain an efficient floorplate that incorporates or drives the unusual form. The variation in layouts, however, can present additional complications for leasing and sales. Speculative developments often require an early buy-in from marketing agents.

3. LEANING TOWERS

It is, of course, possible to create repetitive floor plates within a leaning tower on the condition that the elevator and service core lean with the tower. The two major issues are how to deal with the elevators and the structural challenges caused by the lean.

Leaning elevators are available in the market (refer to Carter B. Horsley, Ottawa elevator changes course, *NY Times*, February 1, 1981), but at a significant cost and performance premium compared to conventional vertical elevators. This constraint often drives the decision to utilize a vertical core and therefore limits the lean of a tower to fall within its own plan footprint at the ground level.

The main structural impact of a leaning tower is the effect of the overturning moment caused by gravity, which causes deflection in the direction of the lean that needs to be added to any wind deflections. Steel structures can be built to a preset geometry such that on completion it will have deformed to its ideal position. Concrete structures are more difficult, as the buildings will continue to lean with time due to the effects of creep. In such cases it may be necessary to oversize elevator shafts to accommodate erection and creep movements.

There are some structural moves that can achieve the appearance of a leaning tower while minimizing overturning forces.

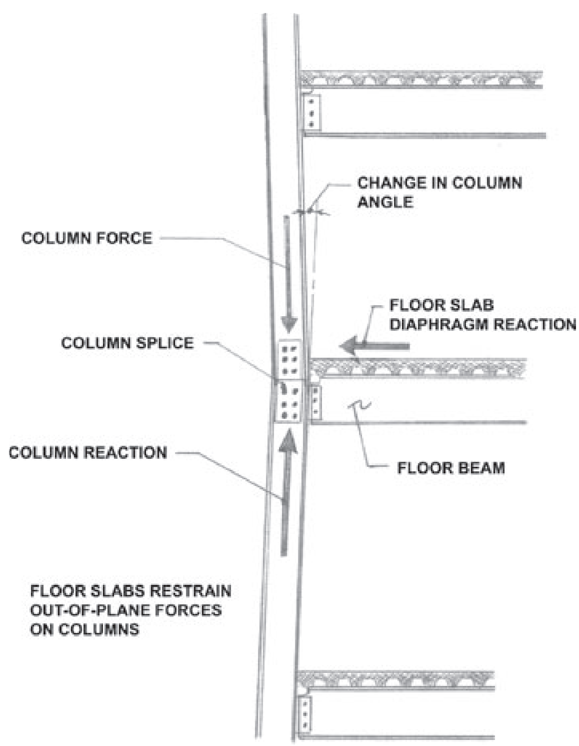

Figure 3. Lateral restraint of columns that kink at floor slabs

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The first is to derive a form for the tower where the overall center of mass of the building is directly over the base where it meets the ground. If this can be achieved then there need not be any additional loads on the foundations compared to a more conventional building. At its simplest form this could be thought of as a requirement for a massing model to stand without lateral support. This can be achieved for some surprisingly complex forms by varying the effective density of different parts of the building (by introducing atria, for example) or by slightly rotating the form at its base.

The second consideration is to allow the loads to travel as near to vertical as possible. If a load due to gravity is carried through an inclined column, it generates additional horizontal forces on the building lateral system. By allowing the loads to travel as near to vertical as possible, these additional loads are minimized. This can be achieved in complex forms by limiting the use of inclined columns and adding cantilevers instead, or by transferring out inclined columns to minimize the loads on them. A highly redundant structure such as a diagrid can prove to be very economical for complex forms, as it allows the loads to naturally find the most efficient (vertical) way to ground through the redundant structure.

A third consideration is the use of symmetry. Symmetric structures by their nature tend to be balanced over their base, and therefore address the first consideration. The impact of using inclined columns can be eliminated in a symmetrical building if the column orientations are also symmetric. In such cases, the additional horizontal forces generated by inclined columns are balanced by equal and opposite forces from the symmetrically opposing columns, and, as a result, there is no net additional load on the lateral system. A very efficient structure can be realized. This need not require that the overall form is perfectly symmetric, as variations can be balanced through the tools previously mentioned—by varying the density of the building, or by playing with load paths by transferring out columns. In such ways, structural symmetry can be achieved even for buildings that appear quite unsymmetrical.

Any practical design will, of course, make use of a mixture of these basic concepts. The Songdo Northeast Asia trade tower is a case in point. The overall volume of the tower is bound by two singly curved surfaces, two sloping surfaces, and two vertical surfaces. The floorplates are driven by the mixed-use nature of the tower and vary from a trapezoid at the base to a triangle at the top, with six-sided floorplates in between. The front and rear surfaces of the tower are curved and sloping; the

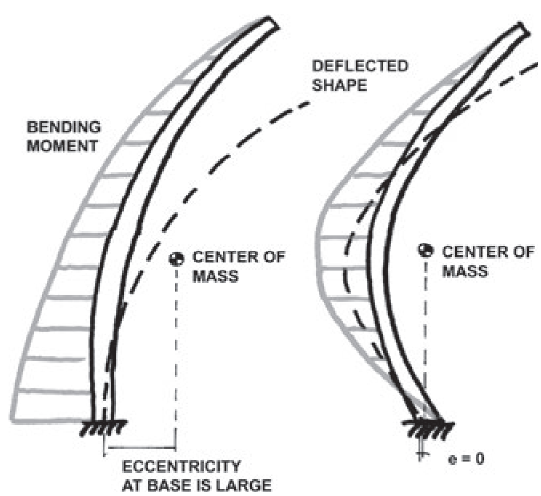

Figure 4. Minimization of overall bending moments through centering the mass of the building over the centroid of the base support

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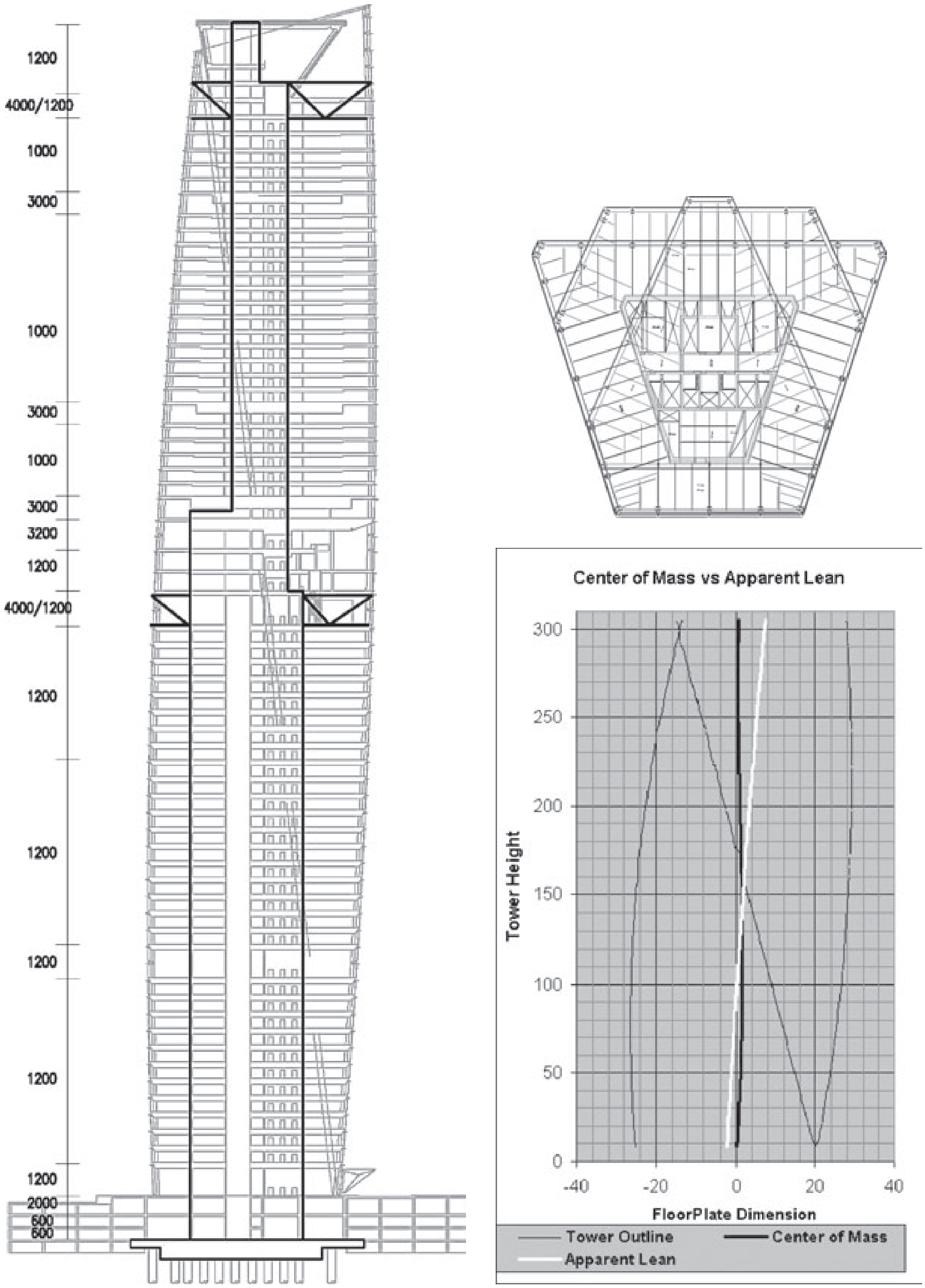

Figure 5. Songdo Northeast Asia Trade Tower: section and overlaid structural plans

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average offset varies along the height of the tower and creates a distinct impression that the overall tower is leaning forward. But because the building changes shape from a trapezoid at the base to a reversed triangle at the top, the centroid of the floor masses actually aligns much more closely than is visually apparent on a side elevation of the building. As a result, the core and foundation see very little overturning moments due to gravity loads.

A more extreme example can be seen in the Libeskind design tower for the 22-story Milan Fiera tower. Here the tower is formed from a section of spherical shell. The curvature, and centroid of the sphere from which it is cut, were varied parametrically to find a form which located the center of mass of the tower directly over the base. This allows a uniform arrangement of foundations. One of the main challenges for leaning towers on soft ground is to translate the overturning of the building into a uniform foundation so that differential foundation settlements do not magnify the lean of the building. The Milan Fiera tower uses a structural steel diagrid system to resist overturning and wind loads by mobilizing the full perimeter structure. The axial forces under self-weight are shown in Figure 6. The diagrid can be preset to take out the effects of self-weight movement. Upon completion the diagrid is finally connected to the vertical elevator core, which is not subject to any lean forces.

4. TWISTING TOWERS

Twisting towers present their own unique problems. For practical reasons the core must typically be vertical and not twisted; however, the relationship between the core and the exterior of the building then changes at every level, potentially creating awkward spaces programmatically. One obvious solution to this is to use a circular core, with a ring corridor, although this will tend to reduce efficiency ratios.

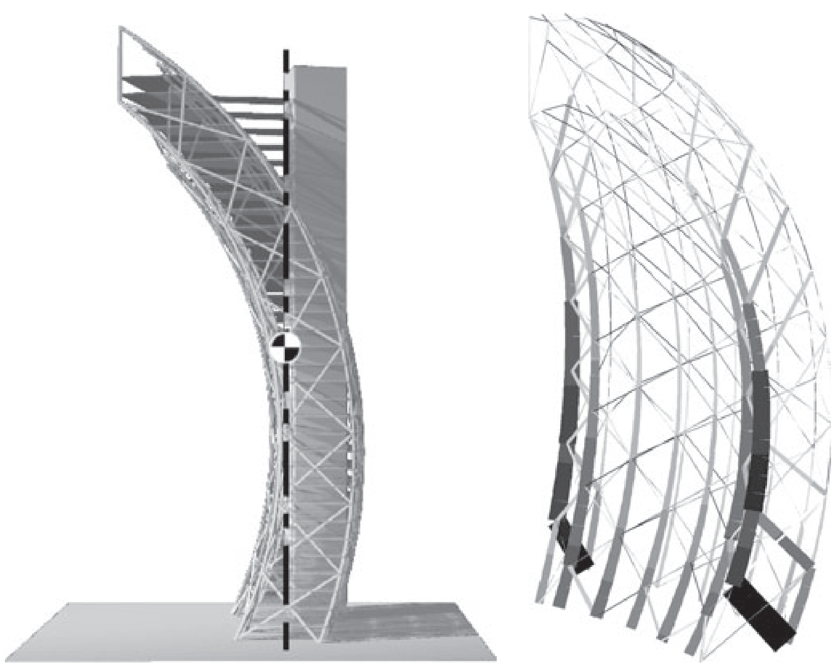

Figure 6. Milan Fiera: side elevation showing center of mass, and force plot

For the building services the challenges are similar to leaning towers, with either sections of programs needing to be stacked, or offsets required at every level. For the structural design the challenges are quite different.

For a twisted tower, if the columns follow the form the only additional forces when compared to a more conventional tower are torsion on the core. To maximize torsional stiffness and strength, it is desirable to maximize the area inside the core, for instance by putting the shear walls outside a ring corridor. For a steel building an external bracing system is desirable. In these cases the thickness of the shear walls or size of elements can rapidly be increased above that required for wind loads alone and parametric studies can help to identify the consequence of varying amounts of twist. As the torsional force is proportional to the load on the inclined columns, it can be beneficial to vary the rate of twist with height.

Another way to approach this problem is to release the columns from the twisting shape of the building, or to add counter rotating columns to balance the torsional force. Indeed it is possible to lean the columns in any direction to generate a desired force to cancel another, provided this can be accommodated architecturally.

An extension to this method is to constrain all the columns to move on radial gridlines, so that for a symmetric form all the horizontal forces cancel each other overall. An example of this is shown in Figure 7 for a competition proposal for towers in Busan by Asymptote. As can be seen, the tower has a substantial twist, yet the columns follow roughly radial grid lines, and therefore there is no net twist on the core.

The same concept of positioning the columns of a twisting tower on radial grid lines is also being applied to the design of another tower in Abu Dhabi by Asymptote. Figure 8 indicates three potential column schemes. Concept 2 indicates the columns following the twisting shape of the tower. Concept 3 indicates the columns as located by a radial grid. Concept 4 indicates columns that run counter to the twist of the overall shape in an effort to balance the twisting forces.

The overall twisted shape of the tower can result in very large structural demands on the building core if the structural column grid is not carefully designed to minimize such effects. Three basic perimeter column options were considered and the geometric effects on critical structural measure-

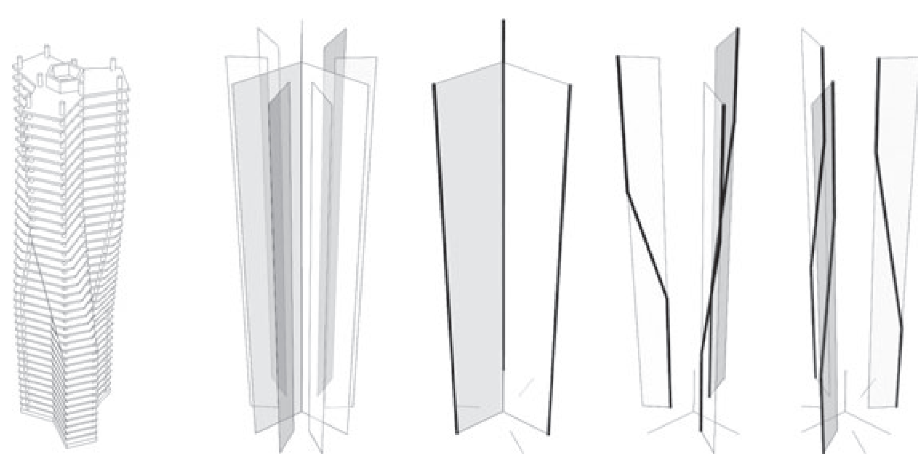

Figure 7. Twisted shape without twisted structure. Left diagram: rotating floorplates create a twisting shape. Right four diagrams: leaning columns that remain in plane with the building center ensure lateral forces are balanced and no torque is generated

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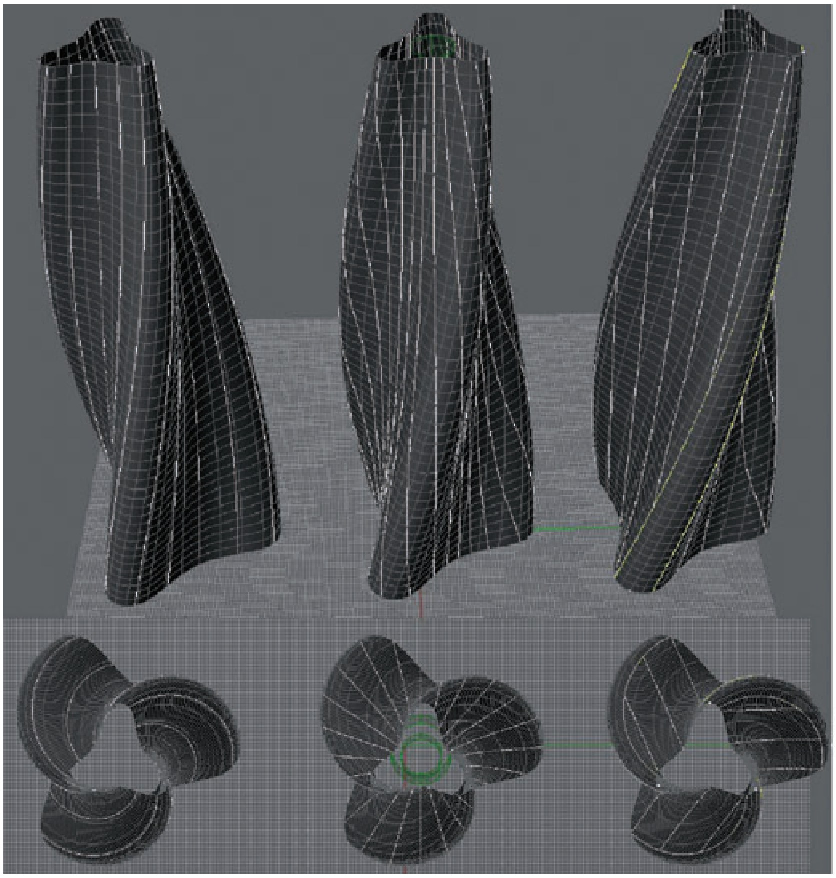

Figure 8. Different options for framing the twisting Al Raha Beach Tower by Asymptote

ments were compared. Figures 9–11 indicate the considerations for each scheme and chart the path by which the eventual decision to go with Concept 3 was chosen.

5. DESIGN TOOLS FOR COMPLEX GEOMETRIES

The design process is changing very rapidly, driven by inexpensive computational power and the knowledge of how to use it. Many standard 3D software packages enable engineers and architects to communicate effectively, but the strongest advances are being made in the areas of computer programming knowledge and parametrics.

Parametric modeling is about creating the rules and dependencies of a building's geometry, while allowing the actual values (e.g., length, width) to be variable parameters, i.e., change the floor-to-floor height in a fixed-height tower, and the model will update and show how many floors can fit in the space. Obviously, this instant evaluation of options has huge advantages over traditional trial-and-error methods. During a normal design process, developers frequently wish to change layouts, headroom, and total floor area, which is notoriously difficult to do on a building whose shape and aesthetics have been set. Parametric modeling can help by allowing the desired changes to occur without upsetting

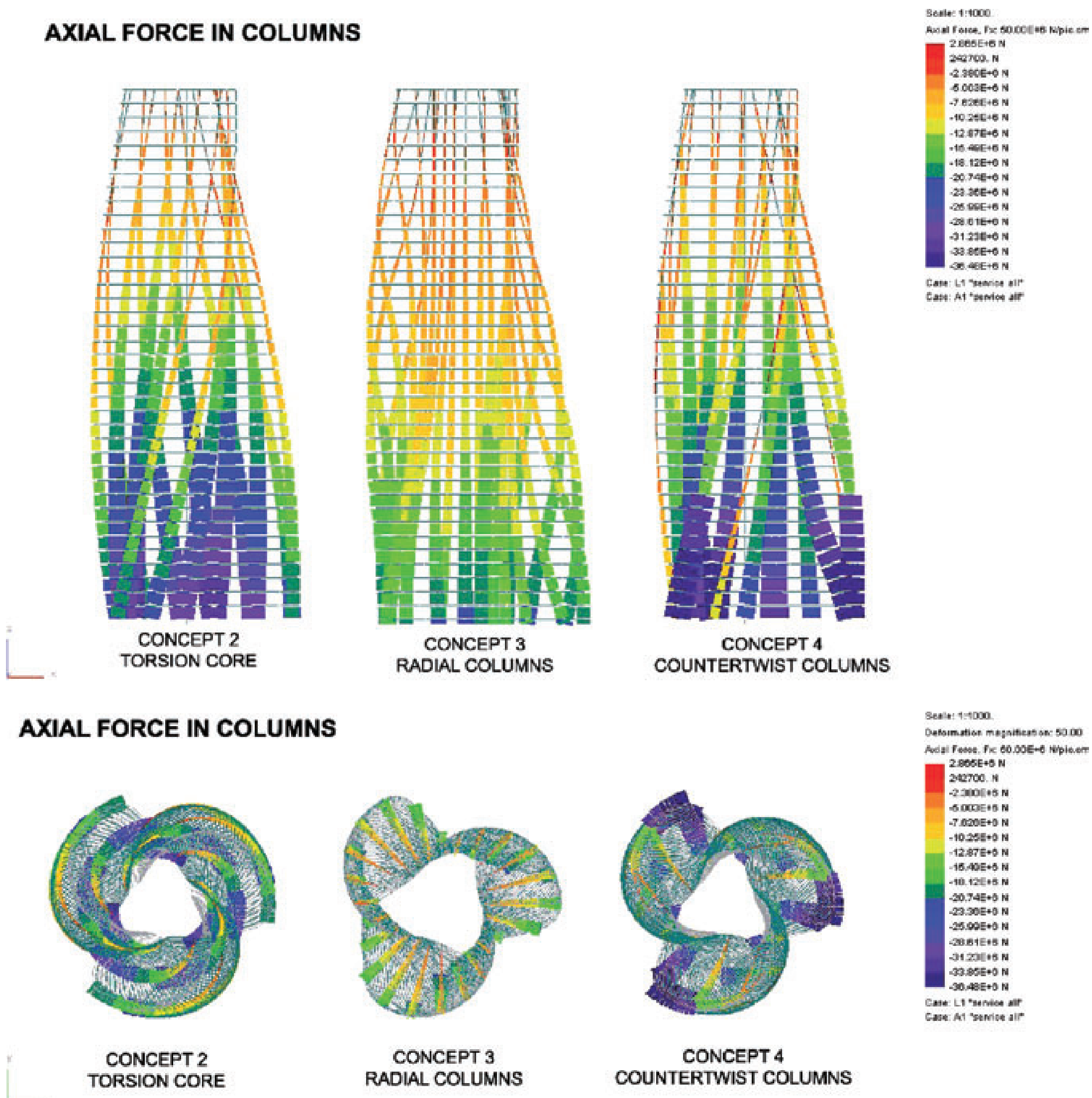

Figure 9. Axial forces in the columns are relatively similar. Additional columns in Concept 3 reduce the maximum axial load compared with that seen in Concepts 2 and 4

the remaining constraints. The rules within the model automatically update all the dependent parts of the building's geometry.

By their nature tall buildings arrive at solutions with simple parameters. The repetition of stacked floorplates always provides a mathematical baseline. A logical progression follows that floorplate shapes then are a function of height, façades are offset from the slab edge, and the dependencies continue until the desired level of detail is achieved. An indicative example of a parametric analysis used to vary the twist of a twisting tower is shown in Figure 12.

A common problem with parametrics is deciding the parameters themselves. They are, by definition, constraints and have to be agreed upon and maintained by all if they are to remain of any use; e.g., new parameters are difficult to introduce once the algorithms have been written.

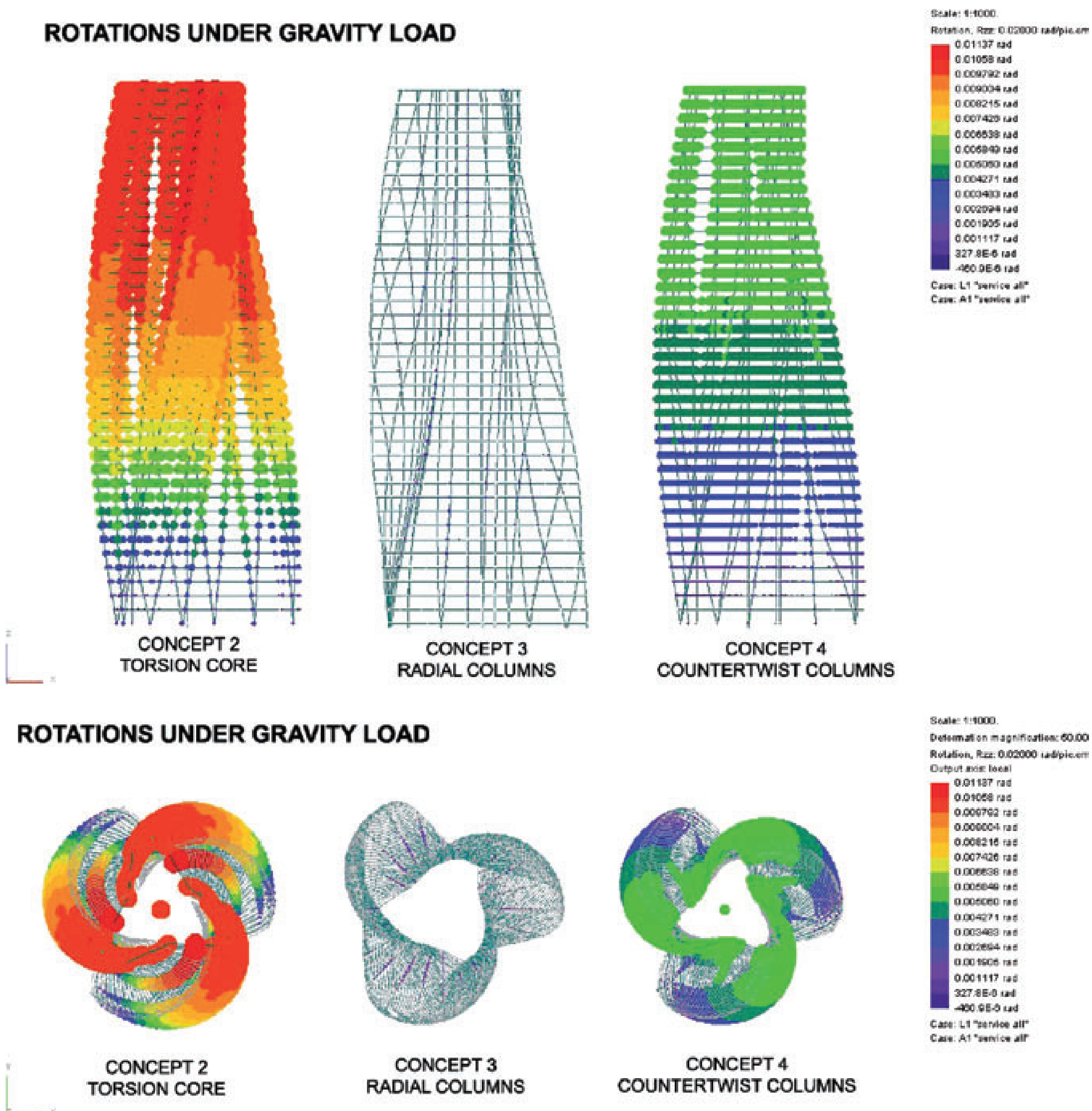

Figure 10. The torsional twist does not exist in Concept 3 owing to the symmetry and alignment of all columns with the centroid of the core. The counter-rotating columns in Concept 4 serve to reduce the rotations experienced by Concept 2

For the structural engineer, a parametric analysis model allows multiple analyses to be rapidly carried out on the same concept, each with a slightly different geometry. Enabling computers to carry out these sensitivity analyses automatically logically leads into the field of computational optimization. An area of engineering that was once restricted to specialists with heavy computing power is now becoming available to the engineer with a Windows-based linear analysis program and some simple Visual Basic skills.

Digital Project and Generative Components are, among others, leaders in a new range of software dedicated to the parametric approach. While Gehry Technologies are focused largely on BIM (build-

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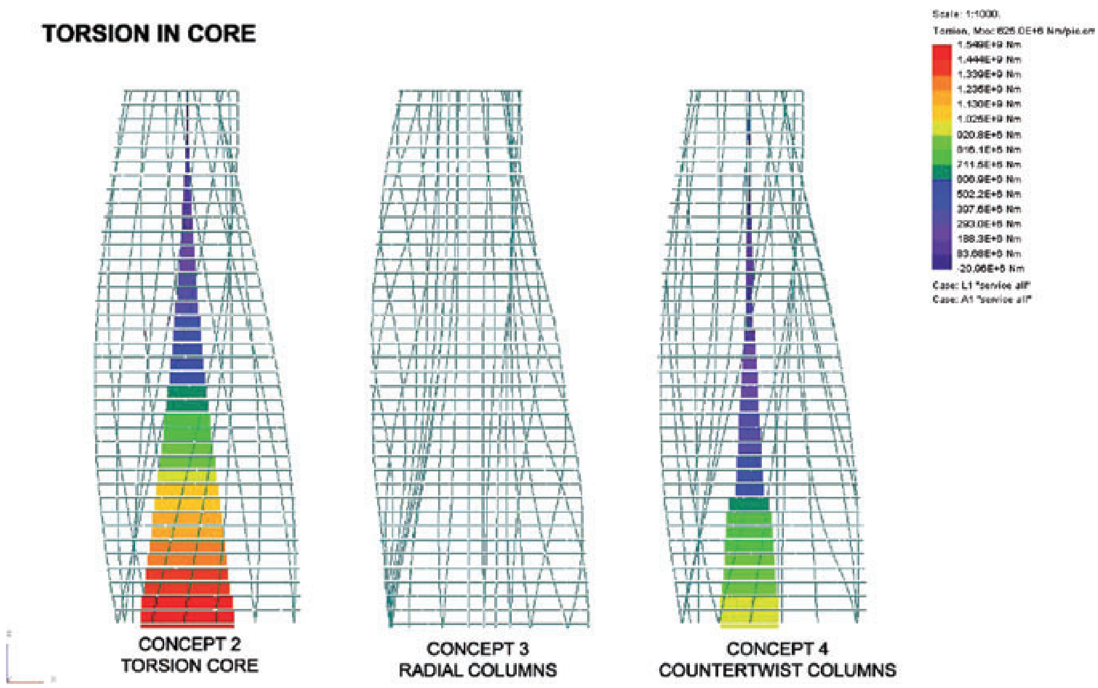

Figure 11. The torsional twist is only resisted by the central concrete core in these schemes. The value of this torsion was very large and would govern the sizing of the main core walls. The most economical solution was clearly Concept 3

ing information management) as far as geometry problems are concerned, their product, Digital Project, is a vehicle to an affordable Catia license, with which comes access to a thoroughbred parametric platform born out of the automotive and aeronautical industries. Generative Components (GC) is a new part of Bentley Microstation that remains a small autonomous tool in the field of pure geometry. For engineers who understand the logic of programming but do not have time to be programmers, GC is a viable solution. The ability of GC to simply create and use arrays is particularly suited to the tall building. With simple rules for a floorplate shape and a height function, engineers can generate twisted, tapered towers. The results are a few paragraphs of readable, editable script and a live updating 3D model.

With tall building engineering, the challenge is not so much the use of these pieces of software but how to streamline the process and pass the data through the various geometry, design, and analysis programs. The structural analysis and design is so important that the software must not be a hindrance to engineering processes. For example, the idea of the analysis model being a simple by-product the BIM model is actually incorrect. The intimate, tiny nuances of achieving a 'correct analysis' for a leaning or twisted tall building cannot be achieved through the interface of a software package that is also managing riser locations and even RFIs. A possible solution lies in the creation of a central database of building features. This database passes information to or from any source, be it sophisticated analysis or engineering intuition, and holds the latest iteration of that data along with the geometry. This script or software that sends or retrieves information to or from the database should not impede the ability of the creator of the information to do its job in the best possible way.

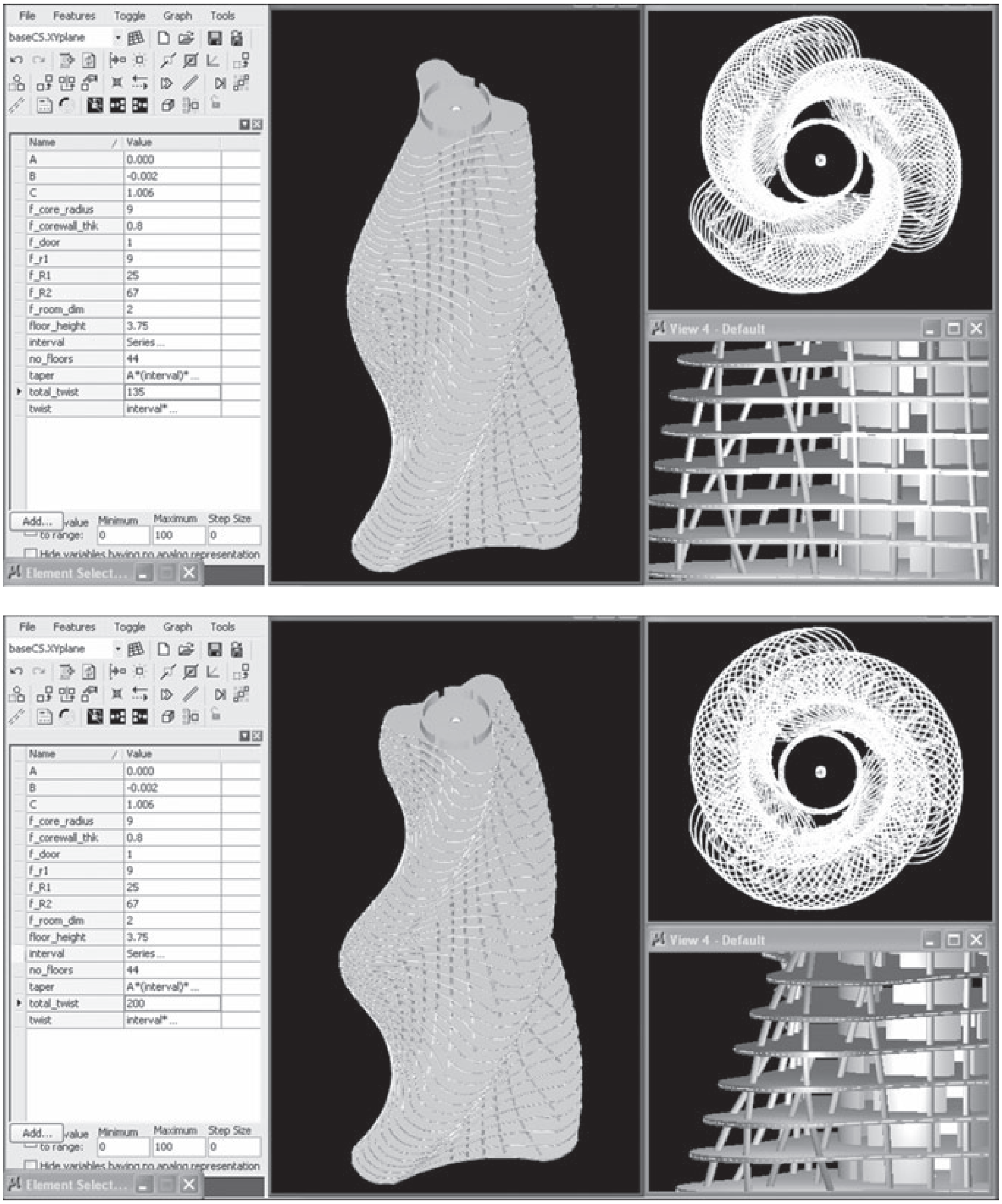

Figure 12. Generative Components model of twisting tower, indicating sensitivity to total twist variable

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6. CONSTRUCTABILITY OF COMPLEX GEOMETRIES

Contractors are using fabrication and production techniques where repetition of form does not reduce the amount of effort in fabrication or erection. For instance, in a tall steel tower every beam knows its individual place, and each is fabricated individually. Thus the CNC cutting and welding techniques used in an extruded form are exactly the same as those used in a tower whose form morphs at every floor level. There is also little additional complexity in the production of fabrication drawings since these can be generated directly from the fabrication 3D models that are produced by either the designers or the fabricators.

Leaning and twisting towers present some additional complications for construction in addition to the purely geometric concerns. If the dead loads of a tower cause lateral deflections or twist, and the tower is made of concrete, then there can be significant complexities involved in both determining and dealing with the creep of a tower with time. Tower designers are used to dealing with differential creep and shrinkage deflections between highly stressed columns and lightly stressed cores in reinforced concrete structures and composite structures. But when the long-term deflections include lateral or twisting movements, these are particularly difficult to predict owing to their dependence on concrete mix designs and construction staging. Other than the need to accommodate these deflections in the internal partition walls and façade joints, a designer may reasonably conclude that the tolerance in predicting them is not important from a visual perspective—if a tower is leaning, there is often no point of reference from which to visually measure the tower's deflected shape.

Despite the capabilities to analytically deal with complex geometries and transfer this information to the manufacturing process through CAD/CAM technologies, it most often proves economical to reduce the complexity of geometry from three dimensions to two. The classic example is the shape of a boat hull. These are often doubly curved surfaces with varying curvature along each axis, but most are framed over a skeletal structure that consists of a longitudinally planar spine and transversely planar ribs. In much the same way, the curving surfaces architects are capable of dreaming up are often sliced up into compositions of planar structural geometry to suit the engineering requirements. The details and connections of structural elements are the clearest indicators of this method's benefits, particularly if the structure is framed in steel. If the structural members can be curved in only a single direction, the fabrication is actually quite simple and the sections can be oriented such that the connections line up to minimize complexity.

The Songdo Northeast Asia Trade Tower provides numerous examples of these strategies. The corners of the tower are framed by columns that pick up loads from façade columns that intersect these corners. In some instances, columns that are carrying 60+ stories are joined together. The connection has been made most simple through orienting the steel sections such that the web plates are coplanar, as shown in Figure 14.

7. CONCLUSIONS

Unusual towers are unlike any other building form ever seen in the world, and it is important for designers to consider the design from first principles, essentially using a performance-based design approach. It is important to remember that building codes have been developed throughout the years using an incremental approach and essentially only cover good practice for normal building forms. It may be quite inappropriate to apply these codes to buildings that are very irregular, and that would certainly not be in the mind of the code committees.

The construction industry has the ability to design and create complex structures without attracting the substantial cost penalty that had previously made this uneconomic for tall structures. This ability creates a new freedom for architects to create some exceptional buildings, but in the process puts

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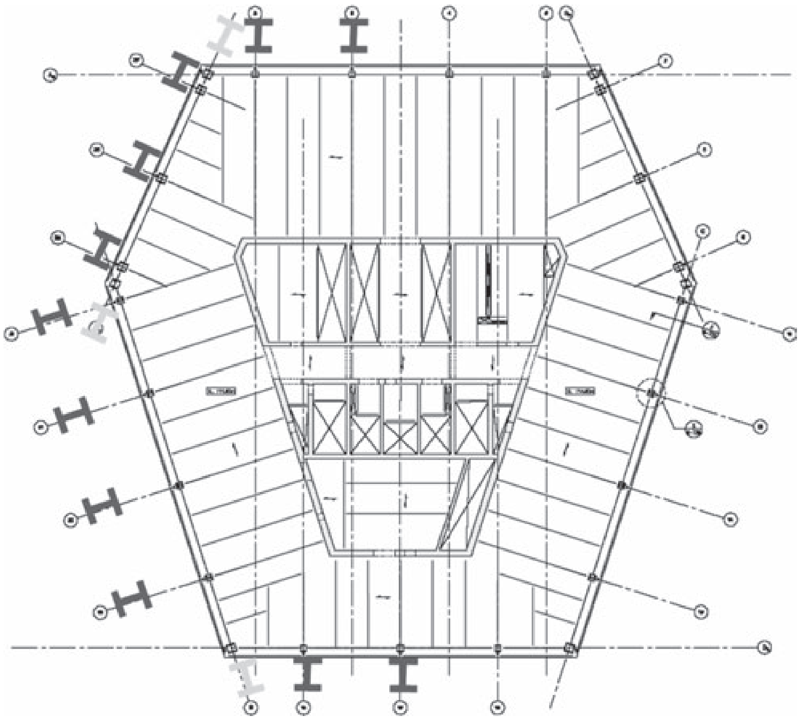

Figure 13. Orientation of column sections for Songdo Northeast Asia Trade Tower

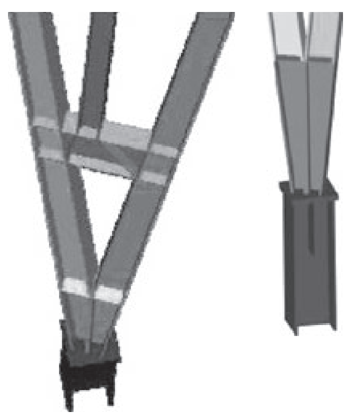

Figure 14. Intersection of multiple rotated columns from Songdo Northeast Asia Trade Tower

greater emphasis on the engineering of these towers in order to adequately address the additional problems these forms present.

One way in which these problems are being addressed is through the use of new technologies and tools described above, but in addition it takes some innovative thinking and novel approaches by engineers. It is imperative that this engineering input takes place at the very beginning of the design, as decisions taken during the early massing studies can have large consequences for the overall cost of the project.

Through the use of appropriate tools, innovative and collaborative design, and modern construction techniques, the limits on what can practically be achieved for tall building geometries has been expanded dramatically. This is beginning to be reflected in the skyline of many cities, and in ever more radical proposals, and quite possibly has opened a new era of tall building design.

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