The Leaning Towers of Vegas

Veer™ Towers, CityCenter, Las Vegas, NV

By Neb Erakovic, PEng, Terry Dawson, BEng, and Kyle Cossette, BSc

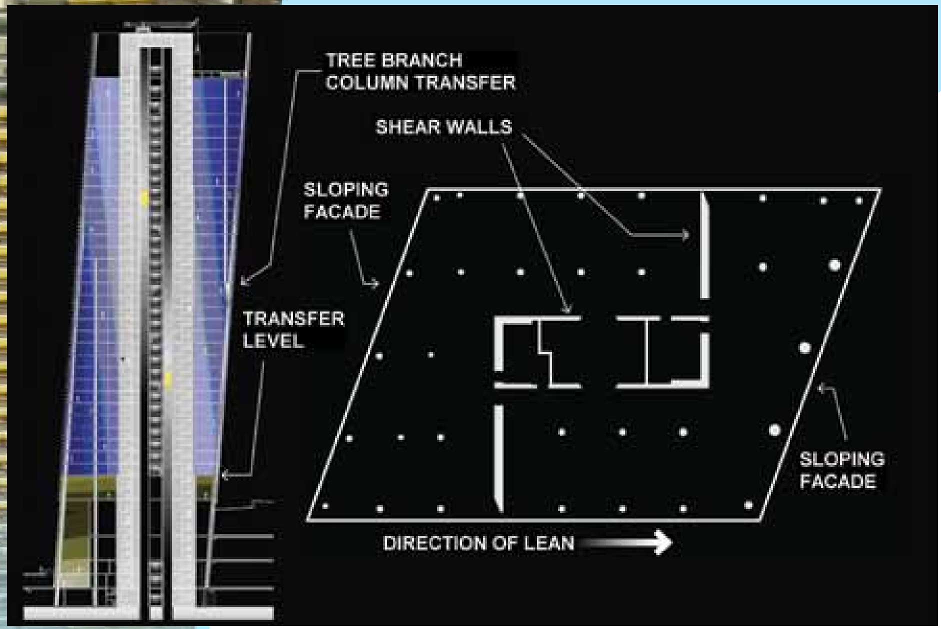


Figure 1: Typical Veer™ Towers Cross Section and Plan. Courtesy of Murphy/Jahn Architects.

Situated in the center of the prestigious CityCenter development, the Veer™ Towers occupy a privileged spot on the world famous Las Vegas Strip. To earn such an honored location, and the moniker *Veer Towers*, these twin, high-rise buildings each lean dramatically at opposing five degree angles from the vertical. The leans, their defining architectural characteristic, required the sophisticated application of conventionally reinforced concrete to the structural building systems.

Halcrow Yolles was selected by MGM MIRAGE to provide structural engineering consulting services for one of three blocks of the giant, 17 million square foot CityCenter project, which is unprecedented in size in North America. Two of the four high-rise buildings designed by Halcrow Yolles are the 37-story LEED® Gold certified Veer Towers. These stunning towers rise 480 feet above the Las Vegas Strip to provide accommodation for approximately 670 condominium units, spectacular rooftop amenity spaces, and podium lobby spaces. As Structural Engineers of Record, Halcrow Yolles collaborated with world-renowned architects Gensler, Murphy/Jahn, and AAI Architects Inc. in the design of this challenging project.

Leaning Towers

Intuitively, a leaning building has a natural tendency to lean beyond the intended angle due to the eccentricity of the weight at the top of the building. Other factors, including lateral earthquake and wind loads, differential axial shortening of vertical structural elements, and differential foundation settlement, increase this natural tendency to lean further. The combined actions can potentially cause building instability or damage to elements of the building. The structural design of the Veer Towers ensures that the towers remain stable, and that movements are within acceptable building code specified limits, to ensure comparable performance to a vertical building.

P-Delta Effects

Due to the tower leans, the weight of the upper floors of the towers is eccentric to the vertical centerline of each tower (*Figure 1*). The P-delta effect of this eccentricity imposes permanent lateral shears and overturning moments on the lateral load resisting system of the towers. These forces try to push the towers further over in the direction of their lean.

Lateral Load Resisting System

The push from the permanent P-delta effects, together with transient lateral wind and earthquake forces, dictates a requirement for a laterally stiff and strong coupled shear wall system for each tower. To satisfy this requirement, shear walls (*Figure 1*) form a large, boxed, 'Z' shaped core on plan at the center of each tower.

Earthquake Loading

Active faults lie beneath the Las Vegas Basin, and the city is located in a region of high seismicity. This high seismic hazard, combined with the tall height and heavy weight of the towers, makes earthquake loading more critical than wind loading for the building design. With the towers already leaning, the occurrence of a major earthquake has the potential to superimpose large additional forces onto the permanently stressed lateral load resisting systems. It is common to use the energy-absorbing benefits of structural ductility to reduce earthquake design forces for buildings subjected to high seismic hazard. However, in the Veer Towers, stiff and strong shear walls are required to resist leaning forces and limit lateral drifts. As a result, a high level of ductility cannot efficiently be used to reduce earthquake design forces, and ordinary reinforced concrete shear walls are utilized.

An earthquake can shake the towers in any direction. If the earthquake ground shaking direction coincides with the direction of the lean of one of the towers, the effect on the lateral load resisting system of that tower becomes critical, as the permanent and transient lateral shears and overturning moments become additive. This is particularly critical on the vertical elements of the lateral load resisting system due to the additive overturning moments. If the side that the tower leans towards is considered the down-lean side, the vertical compression is increased on that side while on the opposite up-lean side of the tower net vertical tension may occur. Thick, heavily reinforced walls are required on the down-lean side, while the net vertical tension requires mechanically coupled vertical reinforcing up the height of the tower walls on the up-lean side.

Differential Axial Shortening Due to Creep and Shrinkage

All high-rise reinforced concrete buildings require assessment of differential axial compression shortening. Long term creep and shrinkage of concrete occurs when permanent or long term loads are applied. Columns and walls both vertically support the permanent weight of the buildings. However, the columns tend to have higher compression stress than walls and interior columns tend to have higher compression stress than perimeter columns. These differences in permanent axial stresses cause the columns and walls to axially shorten at different rates and by different amounts. This differential shortening effect is made worse by the leans of the Veer Towers, increasing compression pressures on the down-lean side of the towers in comparison to the up-lean side. If the down-lean side shortens more than the up-lean side, the tops of the towers will move laterally, increasing the P-delta eccentricity and increasing the leans of the towers.

To allow for the anticipated shortening of the columns and walls, each floor slab is built slightly higher than the final intended design height. This super elevation of floors is common for reinforced concrete high-rise buildings. Despite analyses indicating a preference to super elevate by different amounts across each floor plate due to differential shortening, construction practicalities dictated a need for constant super elevations for each floor plate varying linearly up the height of the towers. Floor levelling compound is applied within each condominium unit to mitigate this potential problem.

Figure 2: South Façade Inclined Composite Lobby Columns under Construction.

Differential Settlement

If the full footprint of a building settles evenly, at the same rate and by the same vertical distance, no adverse effects will be experienced within that footprint. However, unless separated by expansion joints, if one area of a building settles more than another area this difference may cause adverse effects including structural cracking and damage to non-structural building elements. A system of drilled reinforced concrete foundation shafts is utilized to support the towers and limit differential building settlements to acceptable levels. To resist vertical loads, the shafts rely on end bearing onto the dense sand below and surface friction against the sand down the sides of the shafts. The vertical compressive pressure on the sand is higher on the down-lean side and lower on the up-lean side, leading to differential settlement. Similarly to differential axial shortening, this differential settlement will cause the tops of the towers to move laterally, increasing the leans.

The combined impact of P-delta effects, permanent loads, transient earthquake loads, differential axial shortening, and differential settlement, were studied extensively for impact on the leans of the towers. Regular survey monitoring was carried out during construction to ensure that the intentional five degree leans of the towers were not unintentionally exceeded.

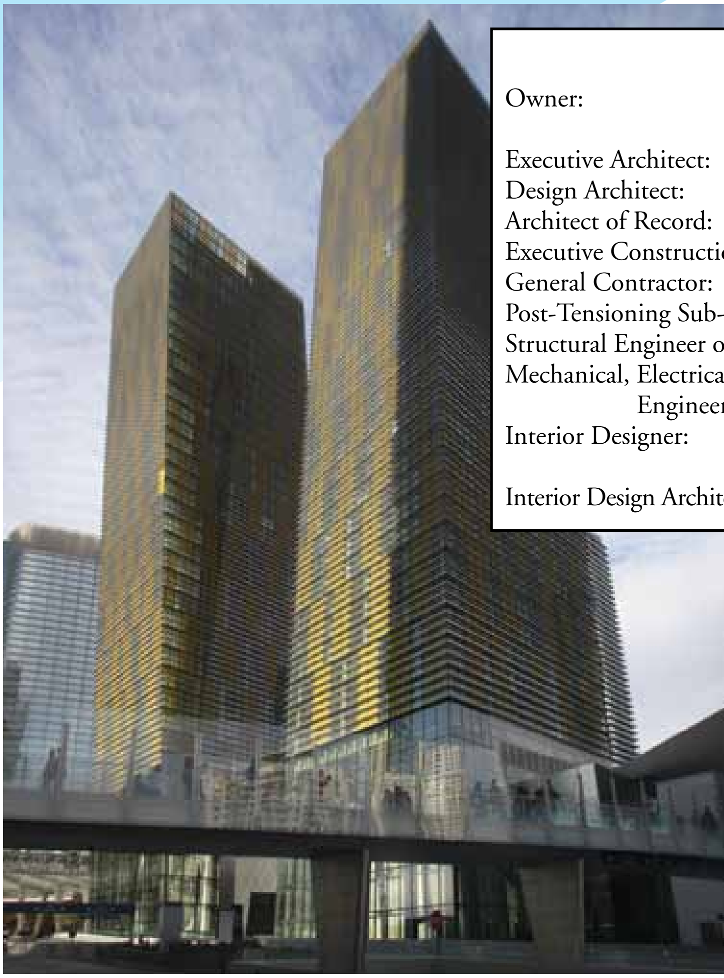
Structural Building Features

Branch Column Transfers

The shear walls and internal tower columns extend vertically over the height of the towers. However, the leans of the towers derive translating floor plates over the height with inclined columns on the sloping north and south building

Project Team

Owner:	MGM MIRAGE, Las Vegas, NV & Infinity World Development Corp, a subsidiary of Dubai World
Executive Architect:	Gensler, Las Vegas, NV
Design Architect:	Murphy/Jahn Architects, Chicago, IL
Architect of Record:	AAI Architects Inc, Toronto, ON
Executive Construction Manager:	Tishman Construction Corp, Las Vegas, NV
General Contractor:	Perini Building Company, Las Vegas, NV
Post-Tensioning Sub-Contractor:	Dywidag Systems International USA Inc., Long Beach, CA
Structural Engineer of Record:	Halcrow Yolles, Toronto, ON & Las Vegas, NV
Mechanical, Electrical & Plumbing Engineers of Record:	Flack & Kurtz, San Francisco, CA
Interior Designer:	Dianna Wong Architecture & Interior Design Inc, Los Angeles, CA
Interior Design Architect of Record:	Hamilton Anderson Associates, Detroit, MI



Veer^{TM} Towers.

façades. Over the 480-foot height of the 37 stories, the floor plates shift a total of 35 feet in the north/south direction. At the sixth, nineteenth and thirty-second floors, column transfers are utilized for the inclined north and south façade columns to maintain feasible spans for the eight-inch-thick flat reinforced concrete floor slabs. Column transfers are tree-branch-shaped (*Figure 1, page 26*) with floor diaphragms reinforced for the resultant horizontal forces.

Inclined Composite Lobby Columns

The south façades of both buildings' lobbies are characterized with 80-foot-tall exposed reinforced concrete columns, inclined to follow the leans of the towers (*Figure 2, page 27*). Due to architectural space constraints for the lobbies, and the requirement to maximize usable space by minimizing column sizes, composite columns with large embedded 'W' structural steel members were introduced at a number of locations. Temporary shoring was required to hold the columns in their correct position until the tops of the columns could be tied into the transfer floor level above the podium. The vertical height and sizes of these inclined columns are large, and required checking for lateral deflections due to self-weight in addition to slenderness, buckling and P-delta effects.

Pre-Stressed, Post-Tensioned Column Transfer Beams

Due to retail and lobby space requirements at the podium base of the towers, a number of tower columns above are terminated at the transfer floor level (*Figure 1, page 26*). A series of large pre-stressed, post-tensioned concrete transfer beams are utilized to support these columns, and to transfer their loads to adjacent columns that continue down to foundation level. The parallelogram-shaped floor plate and architectural requirement for open podium floor plates necessitate transfer beams supported on other transfer beams, creating complex pre-stressing and reinforcement details. In particular, three large transfer beams intersect together at one location. To alleviate reinforcing congestion between heavily reinforced vertical elements and transfer beam pre-stressing anchors and end reinforcing, transfer beams are extended through supporting walls and past supporting columns.

Conclusions

Conventionally reinforced concrete and pre-stressed, post-tensioned concrete is innovatively applied to the structural systems of the leaning Veer Towers. In leaning concrete buildings, there are P-delta effects from permanent and transient loads, differential axial shortening, and differential settlement, all of which can amplify the lean requiring thorough design checks and construction monitoring.

Branched column transfers are readily applied to reinforced concrete buildings, but apply horizontal membrane forces to floor systems. Structural steel 'W' sections can also readily be embedded into tall, heavily loaded reinforced concrete columns to reduce column cross section dimensions. With careful attention to reinforcing detailing, large intersecting concrete transfer beams can be utilized to increase usable space at the base of tower buildings by terminating columns and transferring their loads.

The architectural success of the striking leaning Veer Towers is reliant on an advanced structural engineering solution utilizing stiff reinforced concrete lateral load resisting systems to withstand a natural tendency to lean further than intended.

From an airplane window flying into Las Vegas, from a limousine cruising along the Strip, or from a balcony of one of MGM MIRAGE's other iconic Las Vegas properties, the dramatic lean of the Veer Towers catches the eye and the imagination, drawing visitors into MGM MIRAGE's magnificent CityCenter. The project is scheduled to be completed in 2010.▪

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Applicable Design Codes and Standards:

International Code Council International Building Code (IBC)

American Concrete Institute Building Code Requirements for Structural Concrete (ACI 318)

American Concrete Institute Guidelines for Creep and Shrinkage (ACI 209)