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# Logistical and Structural Design Challenges of the World's Tallest Statue

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*The Statue of Unity, a statue of Sardar Vallabhbhai Patel, is slated to be the world's tallest statue at 182 meters in height. It will be constructed at the Sadhu-Bet Island, 3.5 kilometers south of Sardar Sarovar Dam at Kevadia in the Narmada district of Gujarat, India. Following the conceptual design, planning, and programming of the authors, the project has been successfully tendered and the design-completion and construction began in 2015. The project is expected to be completed in 2018. Logistical and structural challenges associated with the conceptual design and planning were among the many challenges facing this project. Downstream of the Narmada Dam, the Statue of Unity project is surrounded by remote, mountainous terrain presenting extraordinary difficulties. The statue, with exposed feet and lower legs—i.e., inverse proportions to all other large statues—posed significant structural design challenges requiring unconventional structural solutions.*

Under the members of the Executive Committee of Sardar Vallabhbhai Patel Rashtriya Ekta Trust (hereinafter referred

to as “SVPRET” or “the Trust”) a plan was implemented to construct a memorial site including the world's tallest statue commemorating the Iron Man of India, Sardar Vallabhbhai Patel. To initiate the design and construction, a joint venture (JV) team was selected in 2011 for combined design, and project and construction management (PM-CM) services. The JV team included Turner Project Management India Pvt. Ltd, with Michael Graves and Associates as the architects, and Meinhardt India Pvt. Ltd as the multidisciplinary engineers.

The project comprises the 182-meter tall statue of Shri Sardar Vallabhbhai Patel, a 3.5-kilometer highway connecting Sadhu Island to Kevadia, a hotel, a convention center, a memorial garden, and a Visitor Center.

The Trust decided to pursue a design-build strategy and thus the JV team's scope included the concept design along with PM-CM management for the duration of the project.

The iconic statue, standing atop the (recently leveled) Sadhu-Bet Island, approximately 3.5 kilometers south of the

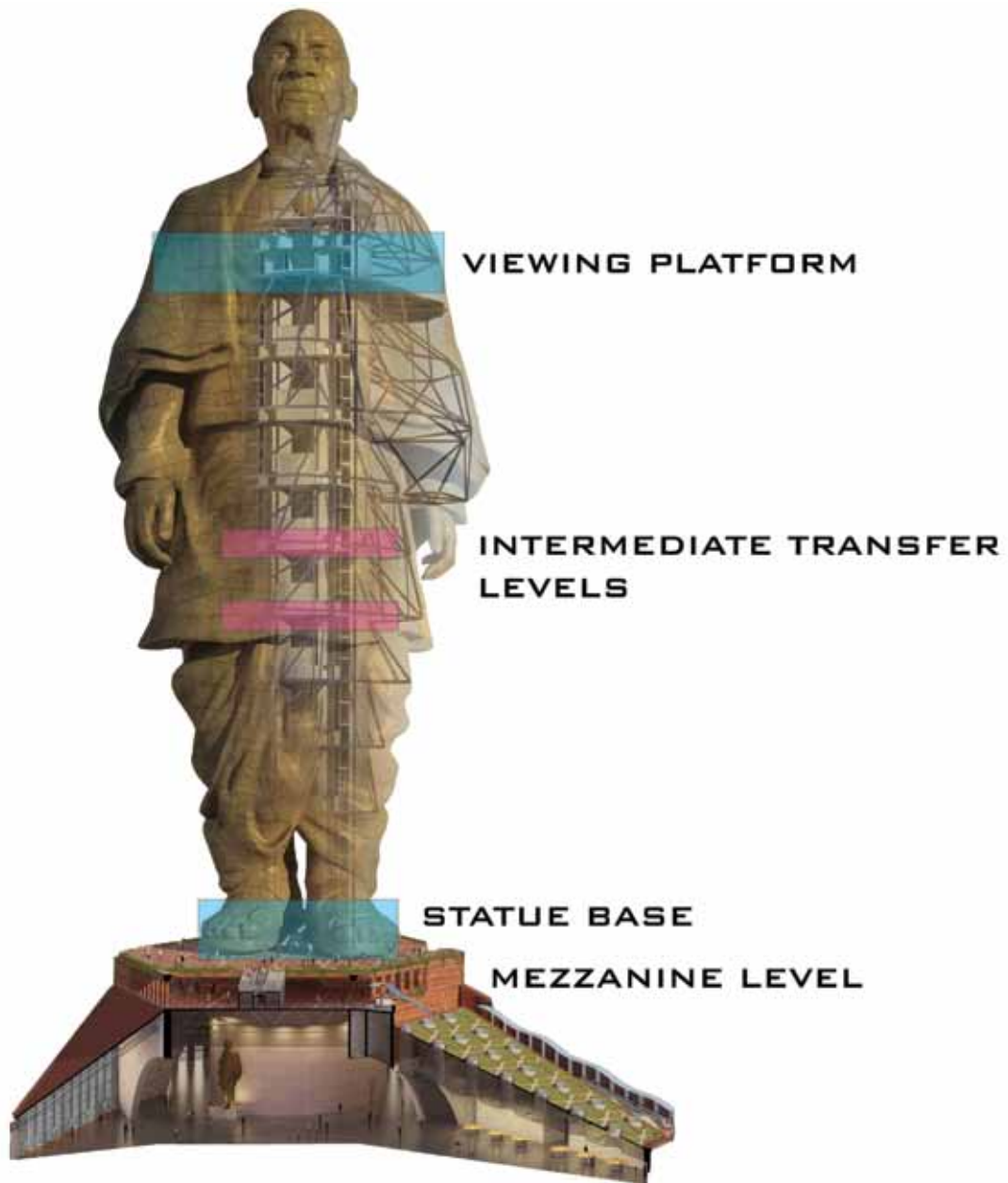
Sardar Sarovar Dam, presents significant design and logistical challenges.

The structural design philosophy, conceptual design, and logistical challenges for the statue itself were examined, as culminated by the JV team from their appointment in 2011, which was built upon previous years of work by the Trust and their site and planning consultants.

The main contractor bid process was completed on October 27, 2014, when the EPC contract was awarded to L&T Ltd. Chennai. L&T, whom, along with their prestigious consultant team, will further develop and enhance the design with oversight from the JV team.

The structure has an irregular curved form that is larger at the top than at the base, requiring a unique but simple and constructible structural system. This was accomplished through the intense collaboration of the JV team, and resulted in a structure comprised of a pair of cylindrical composite concrete cores acting as the primary gravity and lateral system with a suspended space frame to support the cladding.





The statue contains a viewing gallery at the 153-meter elevation, which can accommodate up to 200 visitors at a time and will offer an expansive view of the dam and the surrounding environment.

#### Logistics & Materials

The height and uniqueness of the statue structure would make the design and construction of it difficult in almost any location. In the case of the statue, considering the relatively remote location (a four-hour drive from Ahmedabad or a two-hour drive from Baroda, the nearest airports) and that the statue will be constructed atop a small hillock in a river basin just downstream from the Narmada dam material delivery, staging, and erection also posed unique challenges. As of the writing

of this paper, additional geotechnical testing of the hillock has been completed and the leveling of the hillock has started in March of 2015. The stone removed in the leveling process will be used as backfill where the hillock edges need to be built-up at the edges of the hillock supporting the podium. The hillock has several fracture planes that have been detected which will require remediation, via epoxy or grout injection and grouted anchor rods, as part of the foundation construction.

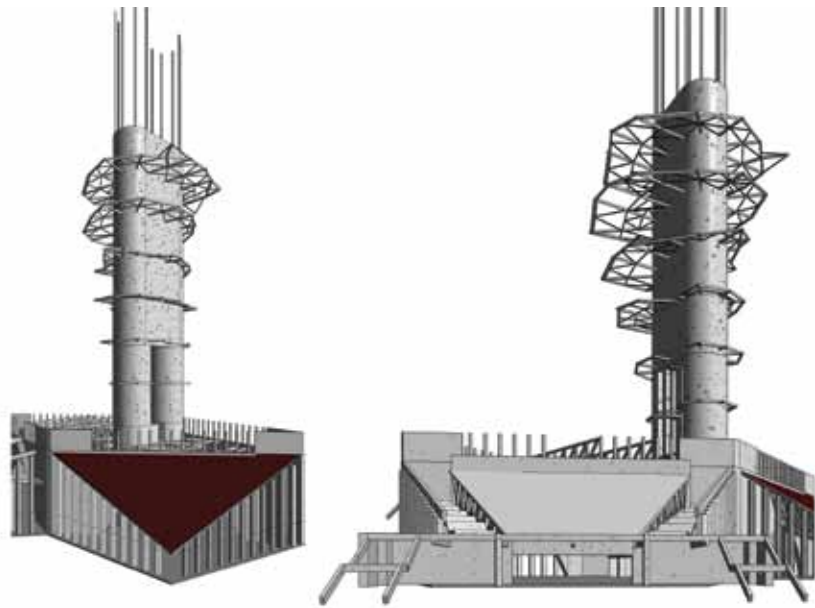
The proximity to the Narmada dam, an immense and monumental structure in its own right, is a considerable benefit to the statue construction. Although very different in the type of construction and materials, the dam's initial construction and subsequent

Opposite: Hillock circa 2013 (left) and being leveled as of early 2015 (right). Source: Turner Construction

Top: Overview of the statue. Source: Michael Graves Associates

Right: Construction sequence space frame.  
Source: Michael Graves Associates

Opposite: Structural connections concepts – core wall to steel space frame connected to composite columns or cast-in embeds and space frame to cladding sub-frame.  
Source: Meinhardt Group



additions has proven that large quantities of high quality concrete can be mixed and placed in this mountainous and remote region. However, the challenge at the site will be in achieving the required concrete strength. Although the dam utilized concrete with a strength of approximately 16 MPa (160 kg/cm<sup>2</sup>) (Charwood, 2009), the design of the statue (including the podium and foundation) calls for concrete strengths from 40 MPa up to 65 MPa (fcu). The statue will require approximately 52,000 m<sup>3</sup> of concrete, reinforced with approximately 12,000 tonnes of grade 500 MPa rebar. Additionally, the statue composite cores, suspended space frame, cladding substructure, and podium framing will comprise approximately 5,000 tonnes of structural steel with a minimum grade of 355 MPa. The structural steel in the cores and space frame of the statue is comprised of W360 (W14) I-shapes. The concrete will be supplied from site batching plants. The rebar will be supplied locally. However, the structural steel will likely be imported.

While the required material quantities are significant, they pale in comparison to the quantities required for the dam construction and the JV team was confident that these quantities could be transported via trucks, barges, and temporary bridges.

Eight months of the year, the island is accessible on at least one side via land as the water levels recede post monsoon season. During the monsoon season, water levels typically rise five meters, and up to 20 meters, with very strong currents.

Several options were evaluated for maintaining access to the island during the Monsoon floods. These included a cofferdam, a rock bridge, and an elevated steel bridge.

Access to the island is planned via two methods. Primarily, a built-up rock bridge which will be constructed at the normal flood level, and then a Bailey bridge will be constructed above the high flood levels. The Bailey bridge will have two lanes, one dedicated to vehicle and material movement, and the second dedicated to worker access.

Laydown and fabrication areas will be established on the land side, near the entrance to the Bailey bridge.

Materials will be delivered to the island via the Bailey bridge and placed via two tower cranes and several mobile cranes.

As part of a 'Loha' campaign, iron tools have been collected from farmers across India with the intent of it being melted and converted into rebar for use in the statue foundation. Thus the people, and in particular, the farmers of India, will be an integral part of statue structure.

### Construction Sequence

Although the structure is irregular, the construction and building sequencing has been made as simple as possible. The composite core construction follows a methodology that is typical for composite columns and walls in tall buildings, while

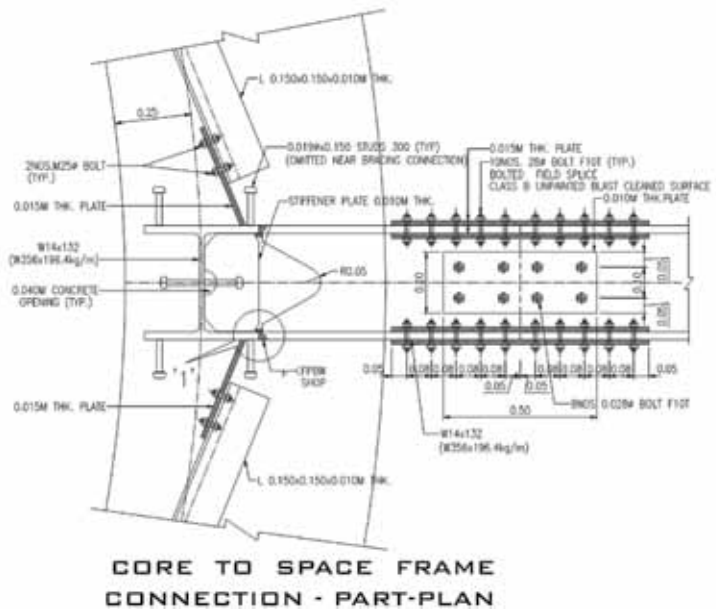
the suspended space frame can be either welded or bolted in place.

For simplicity, the space frame attachments have been kept to a radial module of 45 degrees around the cores, and with a uniform vertical distribution of horizontal primary members at 11 meters. The lengths of the horizontal and diagonal struts are to be adjusted in length to meet the statue's exterior profile. W360 (W14) wide flange structural steel shapes have been utilized for the primary core and space frame members to allow for simple flange-to-flange connections.

The two proposed alternatives for connecting the suspended space frame members to the composite core included:

1. Bolted W360 stubs, shop-welded to the internal steel shapes in the cores, that breach the core wall to allow for bolted field connections
2. Field welded connections to embed plates that are welded to the internal steel shapes in the cores. (These types of connections are typically used for steel beam to concrete core connections, albeit typically with straight concrete walls.)

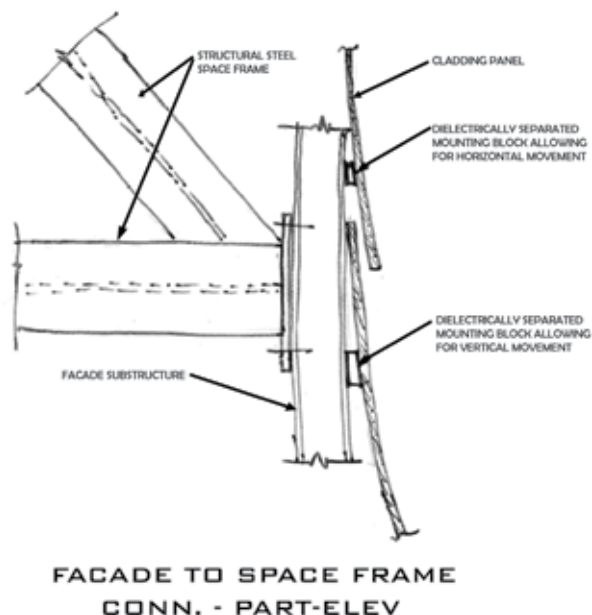
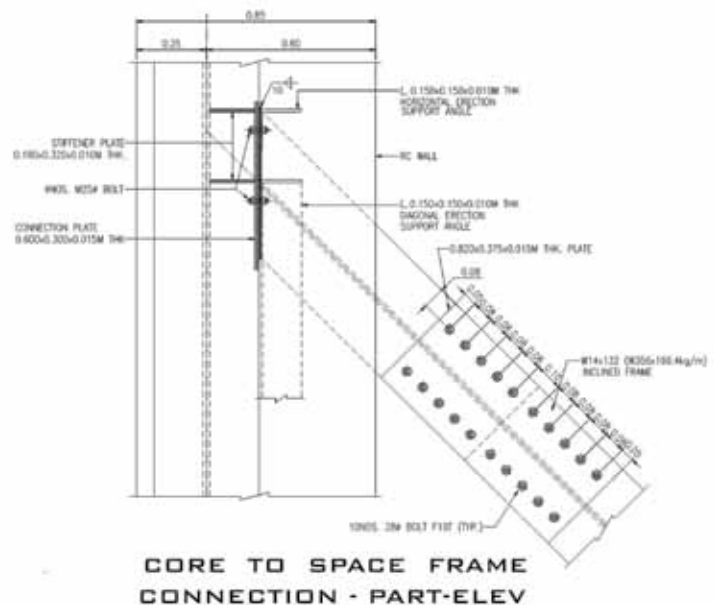
In either case, the W360 shapes are to be interconnected and temporarily braced by 150 mm x 150 mm (6" x 6") steel angles that stabilize the shape prior to concreting the cores. The 150 mm x 150 mm angles geometrically fit within the cores so as not to obstruct the core wall rebar

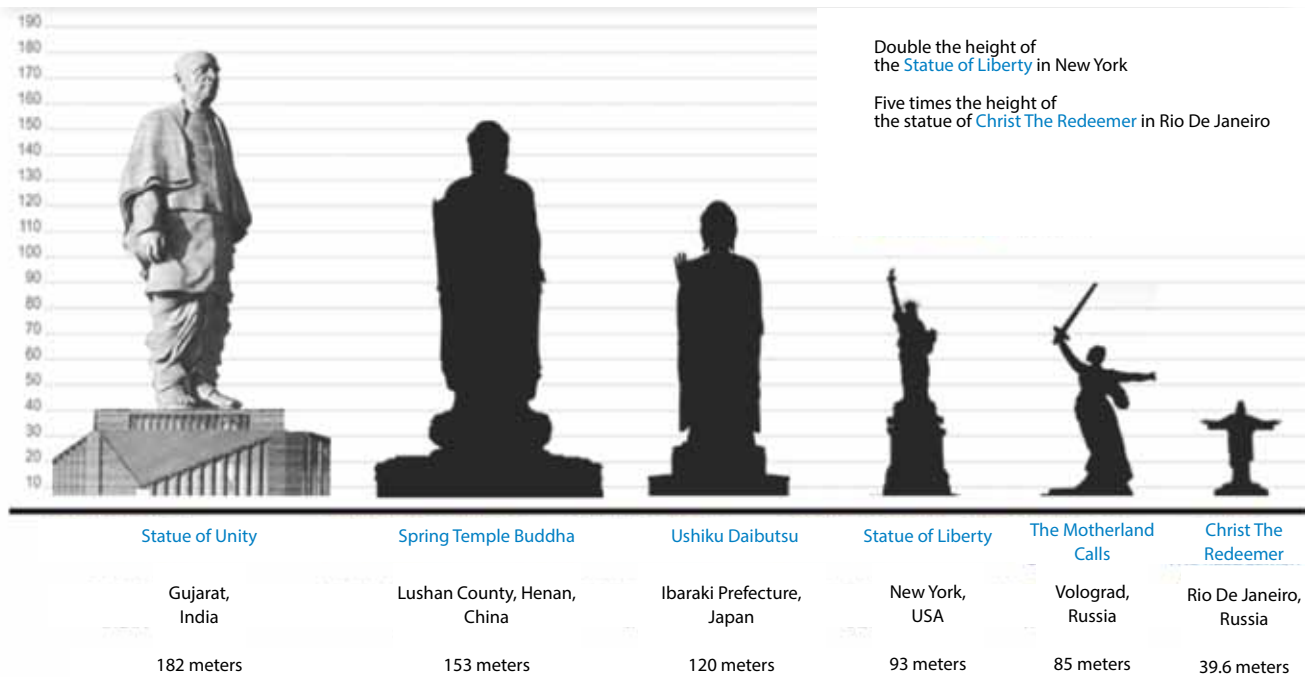


placement. Option One allows for easier field connections, but then dictates a jump-form system, rather than the possible use of a slip-form system which may seem ideal for the cylindrical cores on first consideration. Option Two would allow for slip-form construction, but would create difficulties for the embedded plates to maintain the curve of the cylindrical cores. Considering the geographic location and erection process, the ease of field bolting rather than field welding along the cores was the preferred method and Option One was deemed the better choice. At the exterior of the structural space frame lies a structural steel subframe that supports the cladding. The cladding system was designed to have overlapping panels allowing for vertical and horizontal movements at the panel extents. Therefore, while the subframe will adequately support the weight of the cladding and also resist earthquake and wind forces, the serviceability constraints the panels is less than for typical façade elements. The final cladding material was still under selection and the subframe will need to be considered integrally with the final cladding type by the façade contractor.

Accordingly, the simplified construction sequence has been considered as follows:

1. Level the hillock base to receive the foundation mat (currently ongoing as of the writing of this paper).
2. Inject and stabilize fracture planes.
3. Install rock anchors
4. Cast foundation mat
5. Tension rock anchors





6. Erect the structural steel W360 vertical shapes embedded in the composite core walls
7. Connect the W360 shapes with the internal bracing of the 150 mm x 150 mm (6" x 6") angles
8. After structural steel is erected 5-10 meters above the foundation, begin casting the cores and wing walls.
9. Begin erecting the structural steel space frame from the concrete cores, following the above operations
10. Continue with internal steel work followed by the casting of the cores (by jump forms)
11. Follow the above with cladding installation connecting to the space frame
12. Repeat until completed

Due to the irregular shape the statue was slightly unbalanced for gravity loading. In a conventional building this would require a strategy to compensate for the tendency to lean. Although the contractor will be required to ensure the verticality at completion, given the essentially hollow space frame that supports the cladding, without floors

except at the observation deck, this is not anticipated to lean significantly nor affect the construction sequence.

The cladding will be assembled onto the space frame backup on the ground, with all final alignment adjustments made. The cladding will be removed from the space frame backup, the space frame will be erected into the total framing system. The panels will be moved back to the storage until scheduled for erection on the statue. This process will minimize the requirement for work at height and expedite the cladding process.

### Structural System Description

The key challenge of the structural design was to determine a structural system that could minimize large and undesirable movements inherent to the structure due to the shape and slenderness of the statue's core, as well as adequately resist loads due to gravity, wind, and earthquakes while still allowing the legs and feet to be seen. Considering the varying form, the slenderness ratio varies between 16 and 19. Which is significantly higher than the generally accepted norm of limiting slenderness ratios of tall buildings, which are generally between 8 and 14.

Double the height of the Statue of Liberty in New York

Five times the height of the statue of Christ The Redeemer in Rio De Janeiro

Added to the slenderness is the challenge presented by the large wind loads acting on the statue which, also conversely to most buildings, has a significantly larger wind sail area near the top of the structure. Likewise, the same can be said when considering other tall statues from around the world. Compared to the exposed surface area, most statues have relatively wide bases for lateral stability and to resist lateral loads due to wind and earthquakes (as modified from <http://www.statueofunity.in>).

After considering various options, including options for steel framing only and non-composite cores with a steel space frame, the current system, comprising two semi-joined, cylindrical, composite concrete cores, surrounded by a structural steel space frame to support the exterior cladding was decided on. The structural steel space frame will attach to and hang from the cylindrical concrete cores. The lateral stiffness, constructability, and redundancy of the cores where the primary drivers in the design is not strength.

The concept for the semi-joined cores was a result of the exposed legs of the statue;

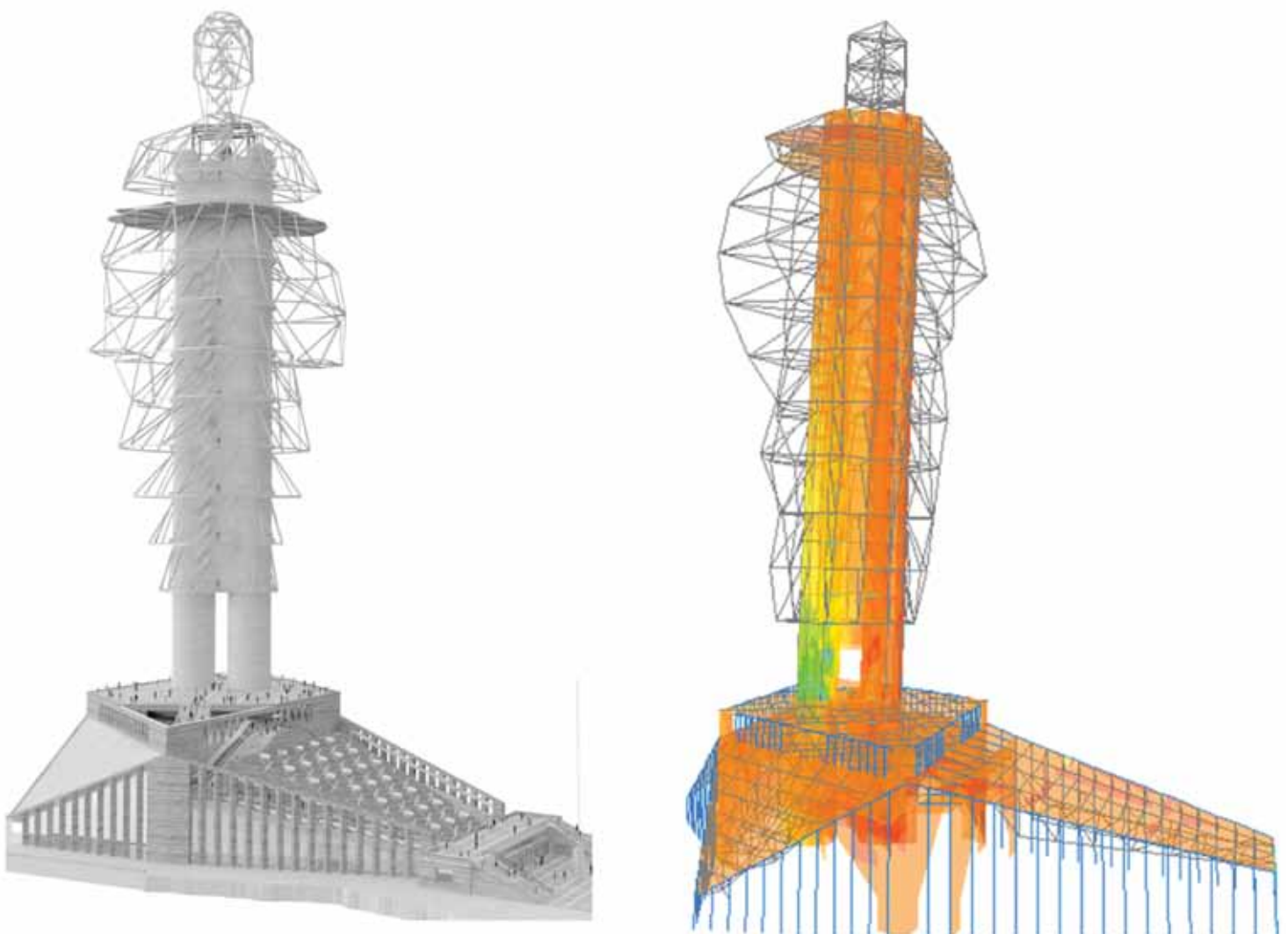
Opposite: Comparison to other iconic statues.

Source: Statueofunity.in

Bottom: BIM and structural finite element analysis models.

Source: Meinhardt Group

*“The key challenge of the structural design was to determine a structural system that could minimize large and undesirable movements inherent to the structure due to the shape and slenderness of the statue’s core, as well as adequately resist loads due to gravity, wind, and earthquakes while still allowing the legs and feet to be seen.”*



while coupled for most of the height, cores remain separate (uncoupled) when passing through the exposed legs. The diameter of the cores has been taken as the extent of the leg diameter. The embedded structural steel shapes within the concrete cores provide a connection for the structural steel space frame to attach to, but also add some stiffness and strength to the system. The cylindrical cores house the lifts and stairs. In the podium levels the cores will be connected to “wing walls” to distribute the gravity and lateral loads to the foundation mat. Each core will have an approximate diameter of 10 meters with exterior wall thicknesses ranging from 850 millimeters to 500 mm with internal and wing wall thicknesses of up to one-meter-thick.

### Codes and Standards

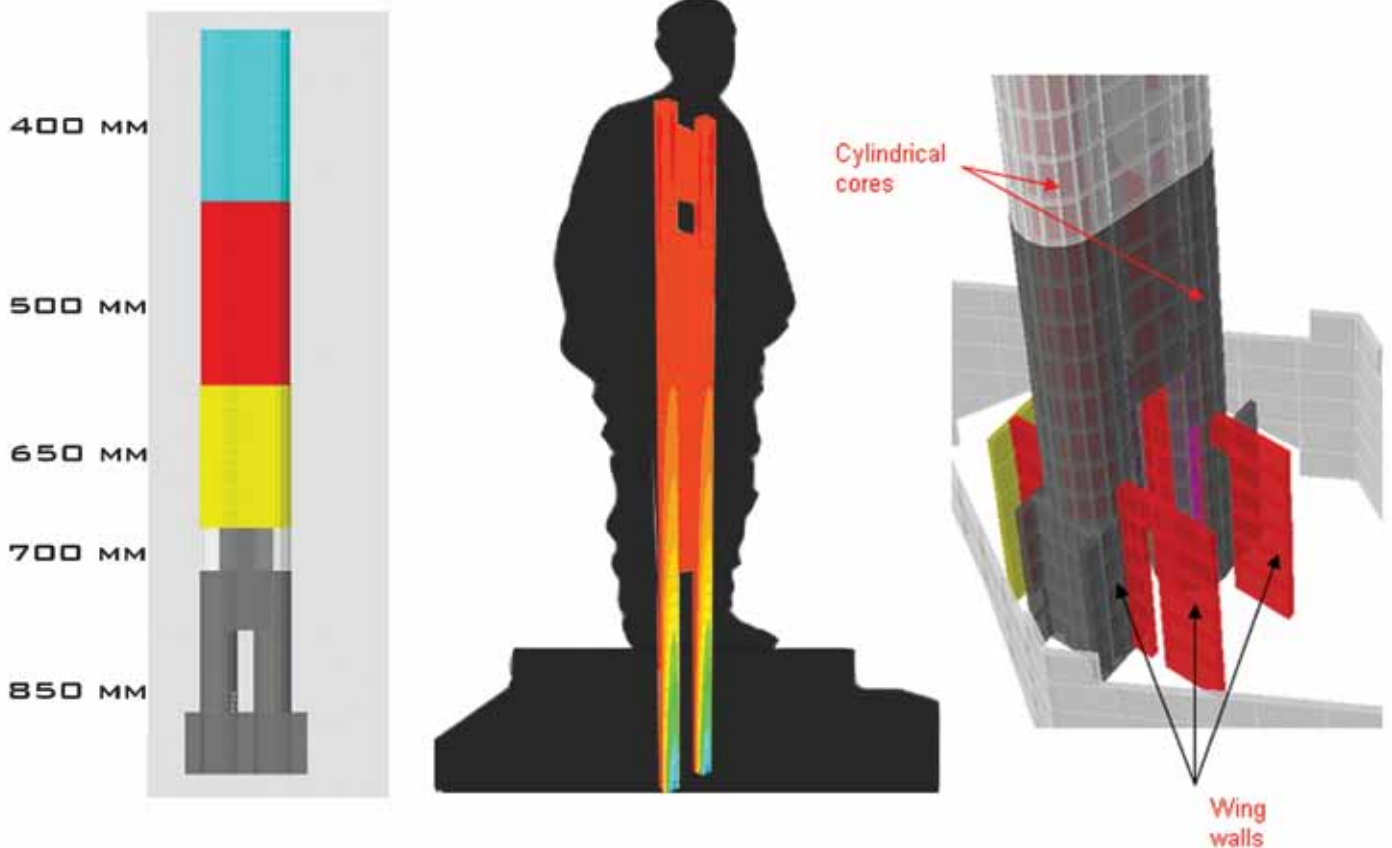
The structural design was carried out in accordance with relevant Indian Standards and in comparison with the international standards, including but not limited to, IS 875:1987 (Parts 1 to 5), IS 1893:2002, IS 456:2000 IBC 2009, ASCE7 10, ACI 318 08, AISC 325 05 as well as will reference to British Standards (BS 7543 for durability considerations) and Australian Standards (AS/NZS 1170.2:2002 for consideration permeable cladding for the structure).

### Redundancy, Robustness, and Durability

The Trust and their advisors were rightfully concerned about the statue’s ability to stand up to the test of time. Therefore, the robustness and durability of the structure were primary concerns resulting in an initial

design that was understandably conservative for these (as well as the design loading).

The statue’s structure is inherently robust and redundant. The cylindrical core walls are robust in that the stresses due gravity are relatively low, and considering an accidental event, would likely only do localized damage to the wall, with the loads redistributed around the damaged area accordingly. For example, in the figures below, a wall panel at the highly stressed “ankle” level has been removed from the cylindrical cores. For gravity loads and even code design lateral loads, the stresses surrounding the missing panel are less than 6 kPa (less than one-tenth of the concrete compressive design strength at that level. Additionally, the coupling walls above the ankles provide additional redundancy.





Opposite: Composite core wall elevations.

Source: Meinhardt Group

Top: Foundation part-plan. Source: Meinhardt Group

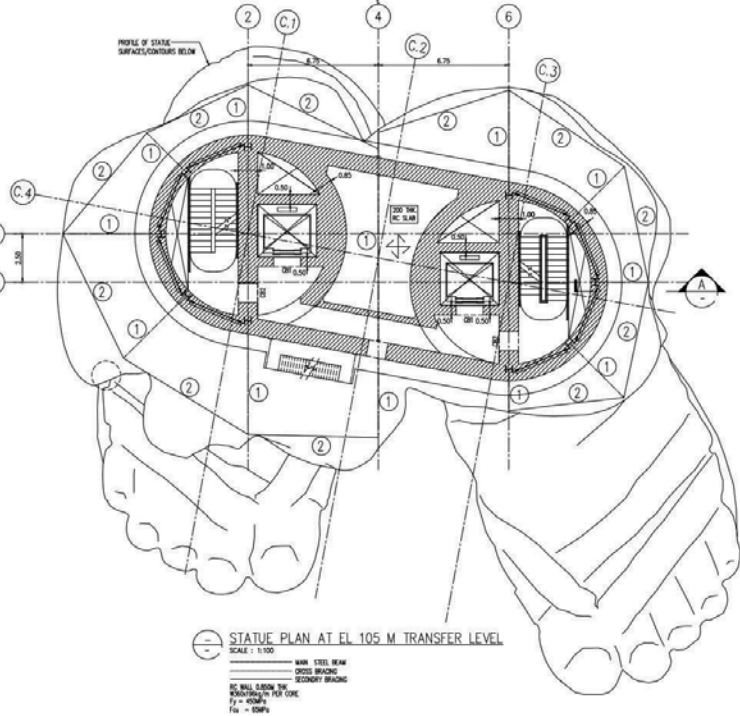
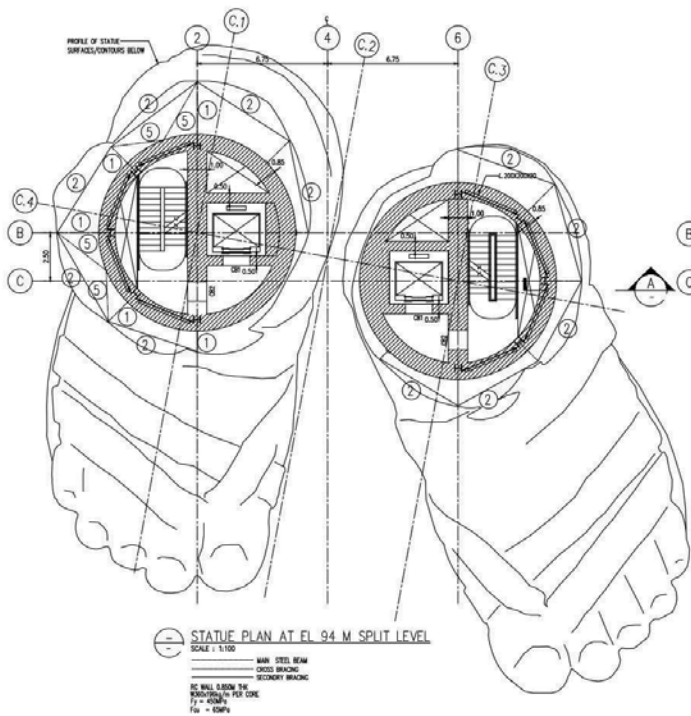
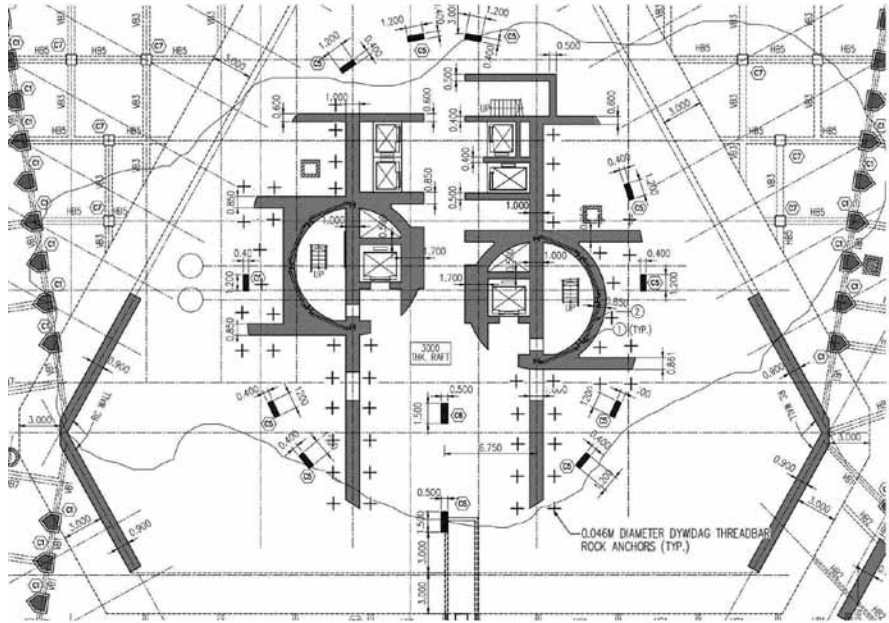
Bottom: Part-plans near the base (feet) of the cores.

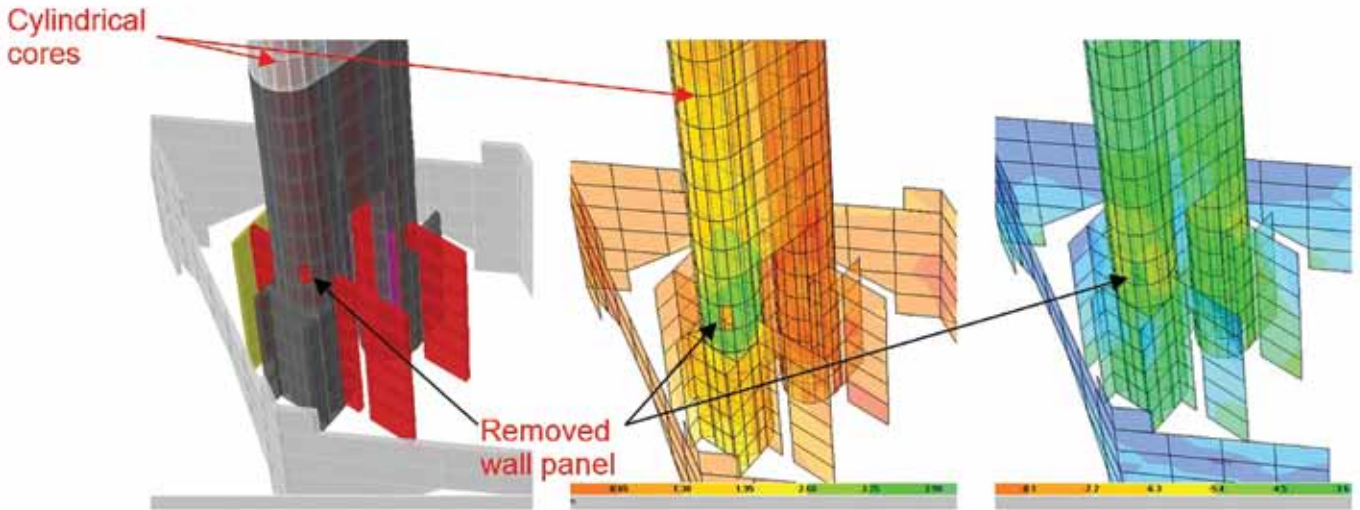
Source: Meinhardt Group

The structural steel space frame members, governed by strength design, were more highly stressed, and thus are not as robust, but like all space frames, are inherently redundant: should a single member fail, there is an alternate load path via the connecting members.

**Structural Design For Lateral Loads**

In following the design philosophy utilized in the Narmada dam and as required by the authorities during the initial design, the lateral load strength design philosophy was generally conservative, utilizing the more stringent of Indian Standards (IS) and international standards, using increased importance factors, considering an increased design life span, and adopting a "code + 1" approach for seismic and wind lateral





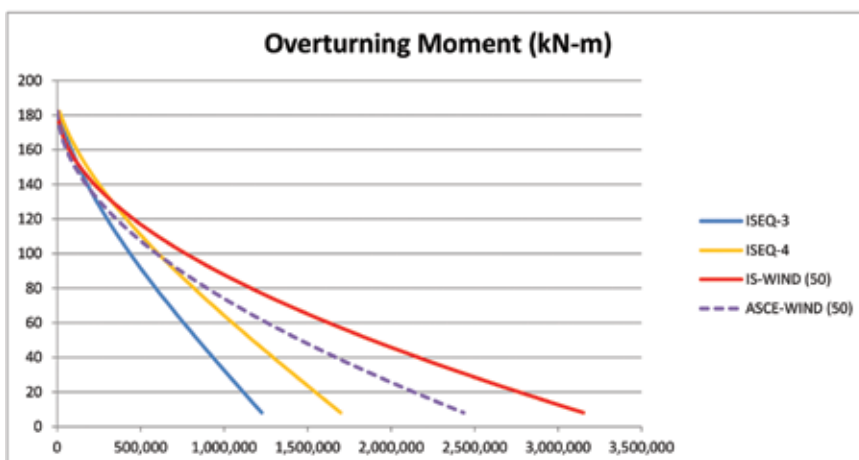
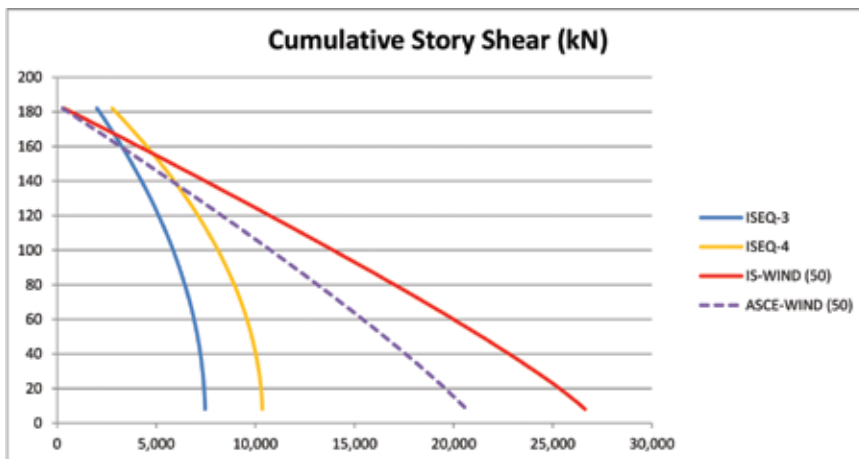
load design where based on geographic parameters. Additionally, a site-specific seismic response spectrum was developed and incorporated into the seismic design. The JV team expects that the “code + 1” philosophy will be reconsidered as the EPC team design progresses.

The statue base was raised above the design flood level of 56+ meters to prevent against flood loads that would arise from monsoon rains or a surge due to a sudden release from the Narmada dam upstream. Additionally flood loads to 63+ meters were also considered, but were found to be insignificant to the overall structural lateral design.

#### Wind Load Determination

Although independent of the final design and wind tunnel analysis, the initial analysis results demonstrated that wind loading, and not seismic actions, governed the lateral load design of the statue. This had to do with the relatively high code-prescribed wind speeds and the statue being a relatively low-mass (mostly hollow) structure with a large wind sail area. To determine this, seismic and wind forces prescribed by Indian Standards were compared with ASCE7 10 based wind forces for the design criteria wind speed of 50 meters/secondas seen in Graph 1.

As shown in Table 1 the following comparisons, the wind loads will govern the lateral load design of the statue. Wind story shears were found to be approximately 2.5 times greater than those from earthquake loads and overturning moments similarly are greater by a factor of approximately



Graph 1: Indian standards seismic and wind comparisons. Source: Meinhardt Group

Opposite: Wall stress contours with a removed wall panel subjected to lateral and gravity loads. Source: Meinhardt Group  
 Bottom: Wind map of India (IS:875 (Part 3). Source: Indian Standards

*“The statue base was raised above the design flood level of 56+ meters to prevent against flood loads that would arise from monsoon rains or a surge due to a sudden release from the Narmada dam upstream.”*

1.5 comparing wind to seismic forces. The following figures, also demonstrate the relative conservativeness of the IS standards as considered in the initial design, and in particular for assumed 50 m/s wind speed.

Wind loads were calculated based on IS 875: Part 3 – Code of Practice for Design Loads for Buildings and Structures. Although the project site is on the cusp of the 44 meters/second to 39 meters/second wind speed range, considering the final geometry and cladding are still to be refined, a conservative, basic wind velocity of 50 meters/second (three-second gust, 50 years return period) was considered (refer to the wind map of India). The more severe of the two estimates using the static method of load estimation (which implies a steady wind speed) as well as the gust factor method (which includes dynamic wind components) of IS 875 were considered for the design.

Modification factors to modify the basic wind velocity to take into account the effects of terrain, local topography, size, etc., have been included as shown below. Wind design parameters for the design are shown below.

Considering the atypical surface geometry, and without the benefit of a wind tunnel test, in order to capture the unique parameters for wind loading, the initial design utilized the code based wind loads incorporated into an approximate surface model from various windward angles using Rhinoceros 5.0 and Grasshopper along with custom components.

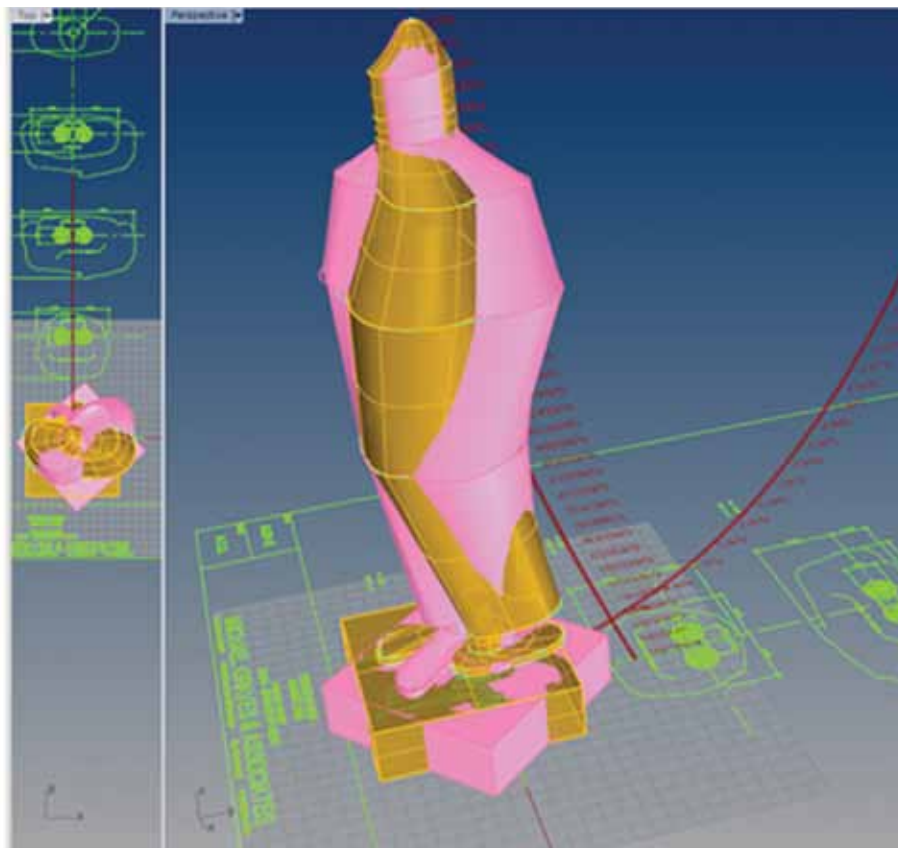


Key Wind Load Design Parameters	Adopted Values	Remarks
Basic Wind Speed	V = 50m/s	Basic wind velocity for Gujarat coastal zones
Probability Factor	$k_1 = 1.0$	For general buildings & structures
Terrain Factor	$K_2 = 1.27$ @ top	For Category 2 Terrain & Class C structure
Topographic Factor	$K_3 = 1.0$	For terrain slope less than 3°

Table 1: Key wind load design parameter comparisons. Source: Meinhardt Group

Left: Rhino modeling for wind loads and corresponding story shears. Source: Meinhardt Group

Opposite: Seismic zone map of India. Source: Indian Standards



The wind force distribution, on the broad (Y-direction) and narrow (X-direction) profiles of the statue, as seen in Graph 2, resulted in a logical distribution considering the statue shape.

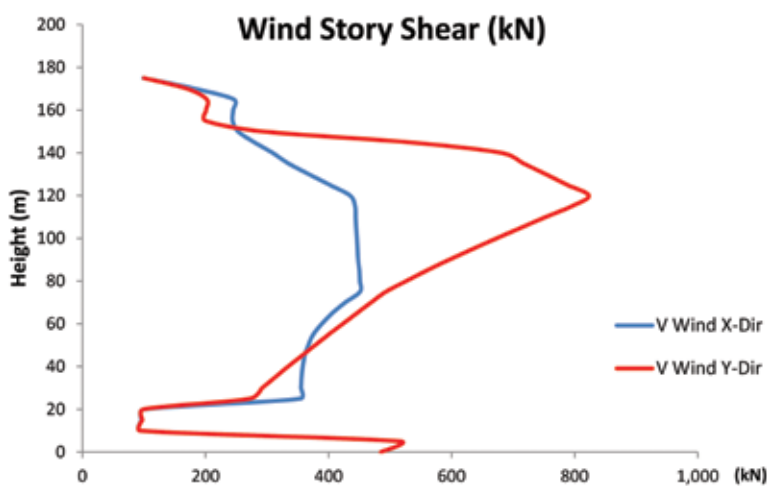
#### Considerations for Permeable Cladding

With wind being the dominant lateral load, due consideration was given to incorporating porous or permeable cladding and also to considering the inherent porosity of the cladding system (conceived as overlapping panels with open joints). Thus, that wind might flow through the cladding and space frame to reduce wind loads was considered. However, after consulting reputable wind tunnel consultants and researching structures with permeable cladding (Robertson, 2002), this tact for attempting to reduce the global wind loads was abandoned. As the design further evolves, however, given the oblong plan shape of the statue, crosswind acceleration is expected to be captured during the wind tunnel testing. Where crosswind effects might exceed the primary windward effects, providing air-permeable cladding in some locations may benefit the performance.

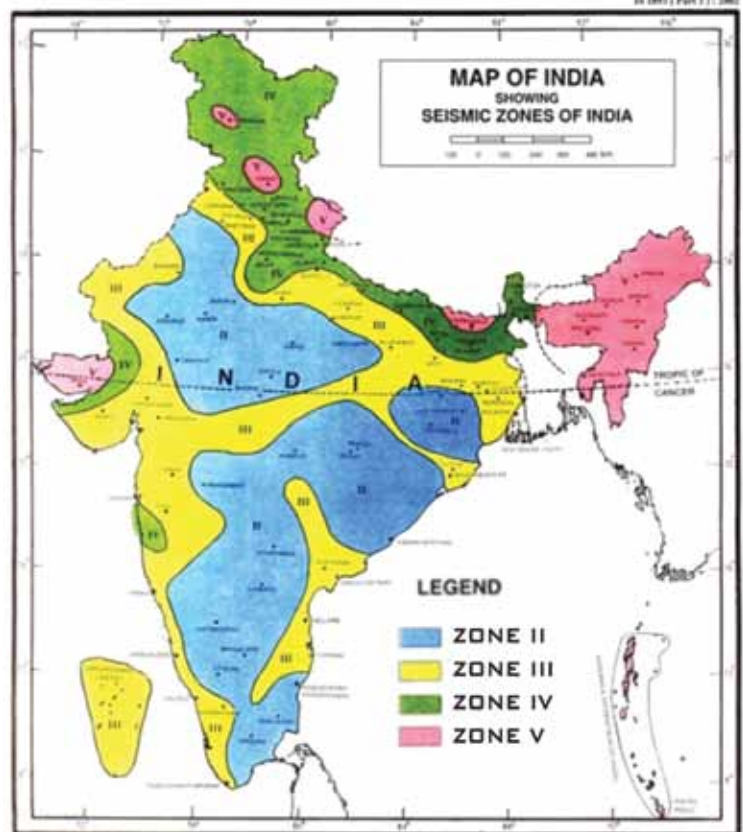
#### Seismic Load Determination

Per Indian Standard IS 1893:2002, the statue site is regarded as a moderate seismicity region and is specified as Zone III. Additionally, the initial geotechnical and seismic hazard assessment classify the IS seismic Zone Factor as III, however, following the "code + 1" philosophy, a Zone Factor of IV has been conservatively incorporated into the design. Coincidentally, the Zone IV peak ground acceleration ( $0.24 \times g = 2.354 \text{ m/s}^2$ ) is essentially the same of as the  $2.36 \text{ m/s}^2$  value specified in the site-specific seismic hazard analysis report, seen in Table 2 (Choudhury, 2011).

As mentioned, due to the relatively high code prescribed wind speeds and the statue being a relatively low-mass structure with a



Graph 2: Wind story shear. Source: Meinhardt Group



large wind sail area, wind loading, not seismic actions, governed the lateral load design.

Additionally, international standards for spectral accelerations from the USGS were also considered as design check. However, the  $S_s$  and  $S_1$  values of 0.11g and 0.04g, respectively (for both UFC and EU Code), also indicated that this was a low seismic risk area.

### Structural Analyses

The structural performance of the statue under gravity and lateral loads utilized several three dimensional structural finite element models. The models incorporated all elements of the lateral and vertical load resisting system and represent the spatial and vertical distribution of the statue mass and stiffness.

### Dynamic Properties

The primary lateral load resisting system is the two composite concrete cores. Whichever way the cores move, so will the rest of the statue. The mode shapes and dynamic periods roughly relate to those of a building of similar height, rationalized for the differences in mass.

The first three natural periods and mode shapes of the statue were tabulated. Similar to tall buildings, the first two modes are predominantly in translation, with some degree of coupled secondary rotation, while the third mode is in torsion. Secondary rotations in the first two modes are manifestations of the irregular nature of the structure.

### Lateral Story Drift

Since the statue is a unique structure, the code or general practice limits for deflections due to wind for buildings (intended to ensure finishes and cladding are not damaged and preserving human comfort) are not necessarily applicable. Additionally, except for the observation deck, there are technically no conventional stories in the statue; however, inter-story drifts (taken at approximately five-meter

Key Seismic Load Design Parameters	Adopted Values	Remarks
Seismic Zone	4	High Zone
Zone Factor	$Z = 0.24$	"Effective peak ground acceleration in 'g'; $\approx$ to Report PGA = 2.36m/s <sup>2</sup> "
Importance Factor	$I = 1.5$	For general buildings & structures
Type of Soil	Type I	Hard Soil
Response Reduction Factor	$R = 3$	Ordinary RC shear wall lateral system

Table 2: Key seismic design parameter comparisons. Source: Meinhardt Group

intervals) were calculated for seismic and wind loads. These were found to be well within drift limits for conventional buildings. Thus, despite of the extreme slenderness of the statue cores above the feet, the adopted lateral load resisting system provided adequate rigidity to satisfactorily control the statue's lateral response.

After multiple iterations involving parametric studies varying the core wall thicknesses, concrete strengths, reinforcing ratios, and structural steel within the cores, the design achieved an overall drift performance well within the norms of conventional design, with the tip of the statue drifting to approximately H/600, which is better than the commonly used in Indian design practice of H/400 or H/500.

We expect that this will be further refined, and perhaps relaxed as more data becomes available in further design stages.

### Supplemental Damping

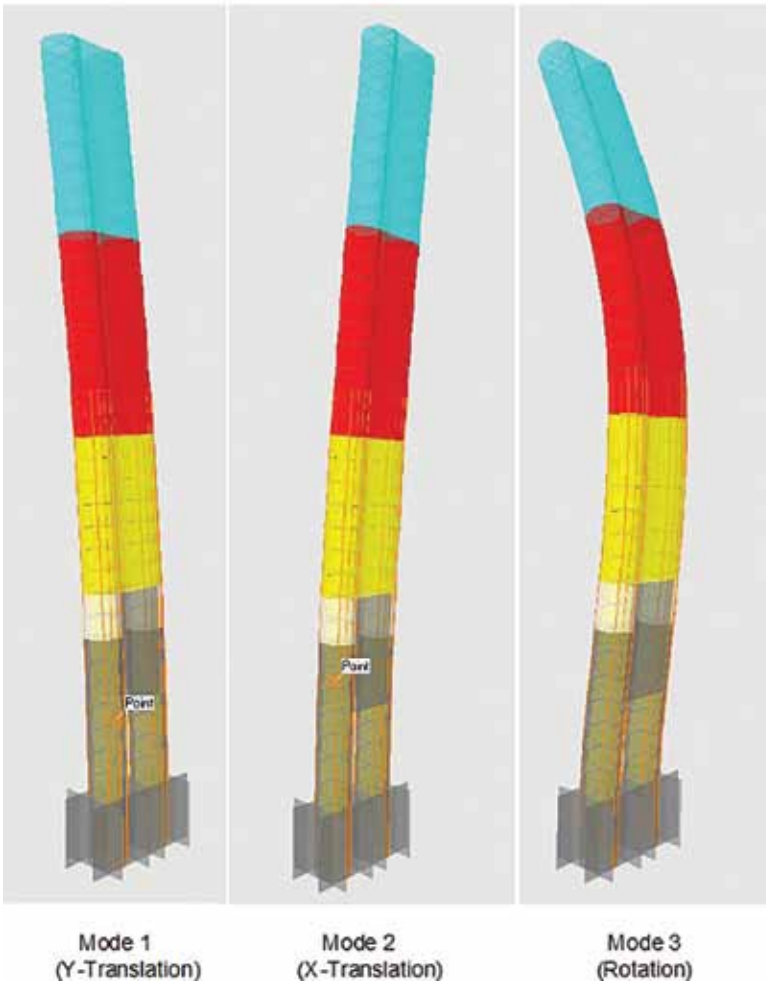
Although the initial lateral drift responses on the order of H/600 would indicate otherwise, the use of passive or active damping was considered as a possibility during the initial design (subject to the wind tunnel analyses). Therefore, space was been allotted in head and neck region of statue for a damper should one be needed as determined by the EPC contractor.

### Strength Design

Generally, the design of the cylindrical concrete cores was governed mostly by stiffness considerations; therefore the wall

Left: Statue mode shapes. Source: Meinhardt Group

Opposite: Rendering of the statue in the context of the plaza. Source: Meinhardt Group



Mode	Time Period (s)	Remark
Mode 1	3.5	Predominant Y-Translation
Mode 2	1.75	Predominant – X Translation
Mode 3	0.81	Rotation

Table 3: Dynamic properties. Source: Meinhardt Group

stresses have been found to be low. However, there are tension forces due to lateral loads at the lower extremes (near the ankles) and these tension forces are carried down through the core wing walls to the foundation. These tension forces were determined to be able to be resisted by the composite cores' reinforcing bars along with the embedded structural shapes.

Contrarily, the structural steel members in the suspended space frame were governed by strength design and were designed accordingly.

### Foundation

In March of 2015, the leveling of the hillock atop Sadhu-Bet Island began in order to

receive the foundation mat of the statue. As the mat sits atop strong rock, piling was not required, but grouted rock anchors to take the localized tensions are required.

There are significant tensions in the foundation due to overturning moments from the lateral loads. These will be resisted by rock anchors socketed into the rock and tensioned at the foundation level. Additionally, measures to stabilize the fracture planes found in the geotechnical investigation, such as grouting and anchor rods across the planes, were also considered.

Based on the site investigation results carried out in 2010 and again in 2013 (WAPCOS, 2013) the average bearing strength of the rock was found to be 2300 kN/m<sup>2</sup>, which is

more than sufficient to support the statue and the associated lateral forces. As this is bearing on rock, settlements were expected to be inconsequential.

### Acknowledgements

The authors would like to thank the SVPRET for their continued support and also RWDI and CPP who both provided valuable pre-wind tunnel input for the initial code-based wind design of the statue.



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