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Cast Steel Node Solutions for Complex Multi-Planar Tubular Connections on NASA Mobile Launcher 2

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Abstract

NASA's Mobile Launcher 2 (ML2) is designed to support the launch of the largest of the upcoming Space Launch System (SLS) launch vehicles, enabling the Artemis program to transport astronauts and heavy cargo to the Moon and beyond. The ML2 structure consists of a vertical trussed tower mounted on a crawler-transporter base, allowing for transport of the tower and SLS Rocket between the Vehicle Assembly Building and the launch pad. ML2 is composed of three primary structural sections: the base of the tower, which integrates with NASA's crawler-transporter and incorporates flame diversion, the lower chair portion of the tower, an asymmetric pyramidal space truss that supports the modules and transitions to the base, and the upper module portion of the tower, consisting of seven stacked rectangular modules along with various umbilical attachments to the launch vehicle. The tower's primary structural elements—18-inch and 24-inch diameter heavy-walled pipe sections—are joined using custom-designed cast steel nodes. These nodes are critical for transferring complex multi-planar loads while accommodating the 3D truss geometry. Designed with both welded and bolted attachment points, the cast nodes improve tolerances and simplify field assembly as compared to a fabricated alternative. This paper provides an in-depth analysis of the cast nodes used in the chair portion of ML2, highlighting their design variations and structural advantages. It explores how these components address ML2's intricate geometric and structural challenges, offering insights into their role in optimizing strength, stiffness, weight, connection geometry, and construction efficiency.

Keywords: lattice structures, metal spatial structures, connections, steel castings, construction/constructability, modular construction

1. Background

Steel castings have long been used in demanding structural connection applications. Cast nodes have been used offshore construction since the early 1980s (Figure 1a), where they offer performance advantages over conventional fabrication of tubular connections. The casting process provides geometric freedom, enabling the creation of monolithic components that accommodate complex, multiplanar, and non-orthogonal frame geometries. These components are typically hollowed to optimize material efficiency. This design flexibility also enhances structural performance by enabling smooth geometric transitions that reduce stress concentrations, while welds are typically relocated away from highly stressed regions to further improve fatigue resistance. [1].

Beyond geometry, the steel casting manufacturing process also provides significant opportunities for customization to meet project-specific performance requirements. Designers can tailor material properties by controlling chemistry and heat treatment procedures, to achieve the necessary strength, toughness, ductility, and weldability. Non-destructive examination (NDE) programs can be adapted to align with the criticality of the application, ensuring that cast steel components are fit for service in even the most demanding applications.

Bridge designers have leveraged these advantages to address fatigue-critical details while also showcasing cast nodes as architectural features [2] (Figure 1b). And in building structures, castings have been used extensively in a large variety of demanding structural configurations, for example as high-performance seismic connections [3], as the central kernel of a built-up mega-frame connection in high-rise construction [4], and in unique grid-shell applications such as the Las Vegas Sphere [5] (Figure 1c).

Additionally, cast nodes are often employed to improve dimensional tolerances during fabrication and erection. The nodes employed on the Sphere, for example, incorporated integral CNC-machined bolted end-plate connections. The tight tolerances of the machined end faces and precision-located bolt patterns were a major benefit of the cast nodes.

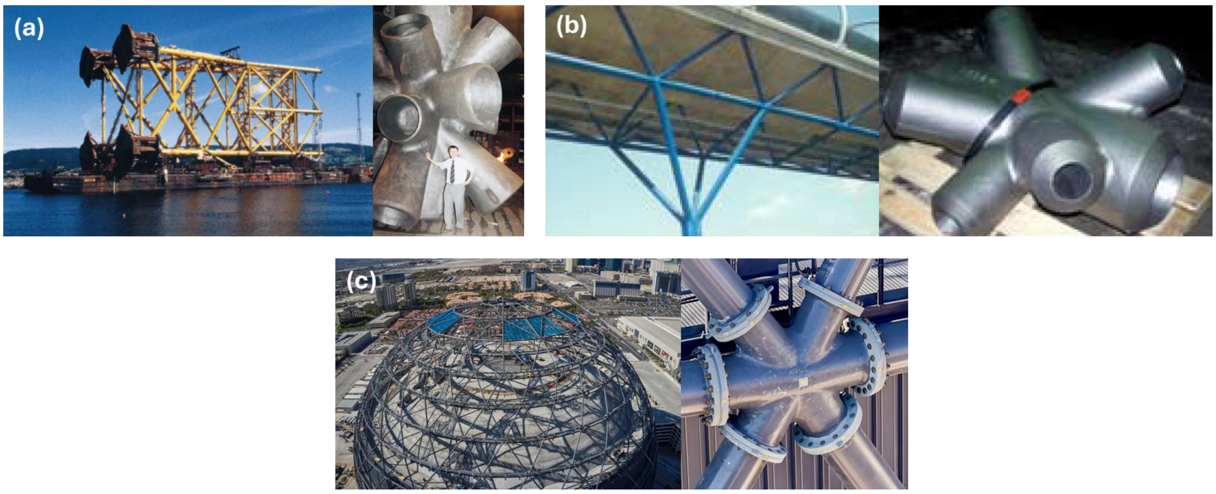


Figure 1: Prior examples of cast nodes in demanding structural connection applications: (a) Ekofisk 24/J offshore structure, 1997; (b) Nesenbachtal bridge in Stuttgart, 1999; (c) Las Vegas Sphere, 2023

These benefits, namely the high structural performance, efficient use of material, quality confirmation with NDE, and improvements to fabrication and erection tolerances, informed the decision to incorporate cast steel nodes into the structural design of NASA's upcoming launch tower.

2. NASA Mobile Launcher 2 (ML2)

NASA's Mobile Launcher 2 (ML2) is engineered to facilitate launches of the largest of the Space Launch System (SLS) vehicles, supporting the Artemis program's mission to deliver astronauts and substantial payloads to the lunar surface. The ML2 features a vertically oriented trussed tower affixed to a crawler-transporter platform, enabling the mobility of both the tower and the SLS rocket from the Vehicle Assembly Building to the launch site. The mobile nature of the tower means that the structural connections were required to be optimized from a weight perspective in addition to being stiff and strong enough to resist the launch-induced loading. Cast connections can be designed with a freedom of geometry that allows for efficient proportioning of steel to meet these requirements, and thus cast nodes were used at the primary structural connection points on ML2.

The ML2 structure is divided into three segments: the tower base, which manages flame deflection and interfaces with NASA's crawler-transporter system, the lower "chair" section, an asymmetrical pyramidal truss that bears the modules' loads and connects to the base, and the upper tower, formed by seven vertically stacked rectangular modules. Figure 2 shows a rendering of ML2, highlighting the modules, chair, and base. This paper focuses on the cast nodes used in the chair portion. While cast nodes were also employed in the module portion of ML2, their design and performance are not addressed here. Furthermore, the scope of this paper is limited to the local behavior, design, and performance of the cast nodes themselves. Broader aspects of structural behavior—such as global deformations, buckling modes, launch-induced vibrations, as well as detailed study of fabricated connection alternatives are beyond the scope of this paper and are not discussed.

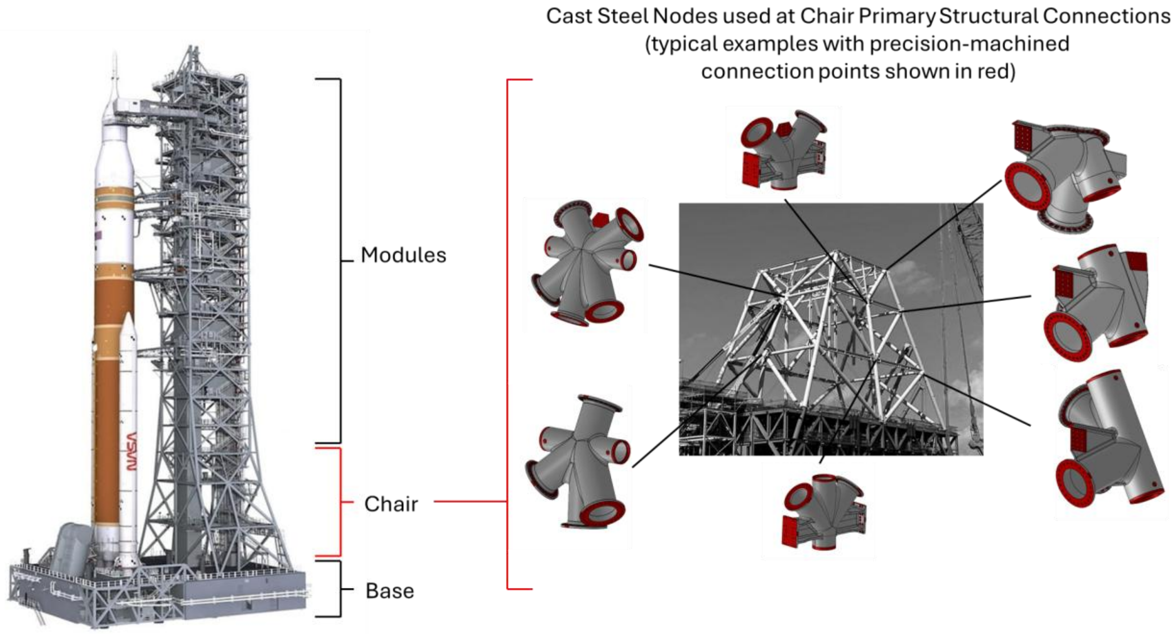


Figure 2: Overview of ML2 Highlighting Cast Nodes used in Chair Portion

3. ML2 Chair Geometry

The chair portion of ML2 is a three-dimensional space truss structure. A total of 20 cast nodes were used at the primary structural connection points. The corner columns consist of 24-inch diameter heavy-walled pipe members (wall thickness ranging from 0.375-in to 2.5-in). At the cast node locations, the corner columns connect to inclined brace members (24-inch and 18-inch diameter pipe members), HSS and wide-flange perimeter beam members, as well as other supplemental structural members (eg.

interior plan brace members). Higher strength steel grades (Fy=70 ksi) were chosen for the primary API pipe members and the cast nodes.

The chair structural form is an asymmetric pyramidal shape, with one vertical face and three inclined faces. Due to the structure's asymmetry, the set of member angles at each connection location was unique, and thus one-off cast node geometries were created for each location. In contrast, in the upper module portion of ML2, repetitive connection geometry allowed for some repetition of cast node geometry.

The cast nodes were designed to accommodate the three-dimensional geometry of the space truss, such that all adjoining members were square cut to their member axes (as opposed to miter cut) and connected via welded or bolted connections. Many of these member intersections were non-orthogonal, and thus the three-dimensional shape of the overall chair structure was defined by the geometry of the cast nodes and the lengths of the steel members running between them, the latter being straightforward to control in fabrication and erection. The cast nodes incorporated CNC-machined connection points which featured machine-level tolerances, greatly reducing shop-fabrication fit up issues and improving erection tolerances.

4. ML2 Chair Node Design Approach

The cast nodes were designed to address and accommodate the following requirements associated with this unique structure:

- Low weight was important due to the mobile nature of ML2
- High stiffness and strength were required to address:
  - launch-induced loading
  - gravity loading
  - hurricane loading
- Welded connections were utilized to accommodate the shop-fabrication scheme
- Bolted connections were utilized to accommodate the field erection scheme

The freedom of geometry associated with casting manufacturing allowed for the creation of part shapes that simultaneously addressed each of the criteria noted above. The primary tubular connections were designed as fully fixed moment connections, thus improving the global stiffness and strength of the tower, while the nodes were hollow and thus optimized from a weight perspective. Connection points to adjoining members were integrated into the cast nodes as either bolted or welded connections, as determined based on the shop fabrication and erection scheme.

Shop fabricated "corner-column-trees", "interior frames", and "beam assemblies" were created via circumferential CJP welds between the pipe members and cast nodes, ensuring column strength and stiffness continuity along the length of the corner-column-trees. These assemblies were then field-connected to the primary chair beam and brace members via bolted end-plate connections. The cast nodes incorporated integral bolted end-plates that were designed to connect to the adjoining pipe members via cast flange fittings, which were shop-welded to the ends of the adjoining pipe members. While conventionally fabricated bolted end plates (consisting of plates welded to the ends of members) are susceptible to distortion from the heat of welding, the cast integral flange plates and cast flange fittings provide precision-machined milled-flat end faces that offer a high dimensional tolerance and flatness which improves fit up in the field. And while thick steel plates welded to the ends of members can be susceptible to lamellar tearing, lamellar tearing is not a possibility when cast flange fittings are utilized.

Figure 3 presents an overview of the typical fabricated subassemblies for the chair structure. The corner-column-tree assembly incorporated three cast nodes (level 30, 60, and 80 corner nodes) each, which were complete joint penetration (CJP) shop-welded to the adjoining 24-inch diameter pipe members.

The interior frames consisted of pairs of nodes connected via CJP-welded 24-inch diameter pipe members. These "Y-Nodes" were designed to connect to diagonal braces via integral bolted connections, as well as to wide-flange beam members via bolted end-plate connections. The beam assembly nodes were welded to 18-inch diameter tubular members and accommodate integral bolted connections to the various 24-inch diameter brace members surrounding each node.

5. Example Nodes

5.1 Level 080 Corner Node

The Level 080 corner node shown in Figure 4a connects the chair and module portions of ML2, accommodating the geometric transition between the chair's 24-inch diameter inclined columns and the module's vertical 24-inch diameter columns, as well as the shift from the chair's 24-inch diameter doubly-skewed primary brace members to the module's 18-inch diameter planar braces. This connection also integrates the module bolted connection (MBC), which enables field-stacking of the modules onto the chair during tower construction.

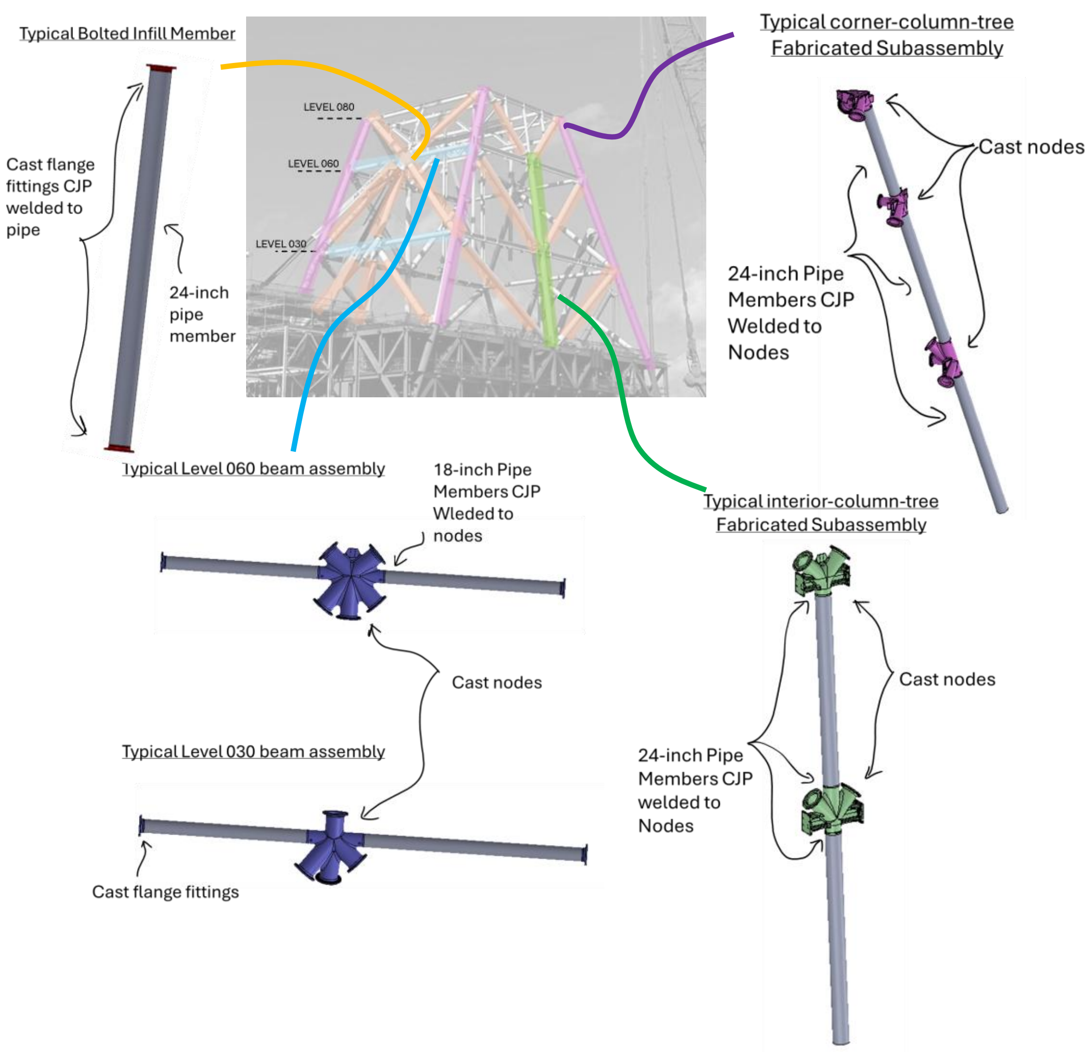


Figure 3: Shop-Fabricated Steel Frame Assemblies Incorporating Cast Nodes

The three-dimensional complexity of this junction, including the MBC, rendered conventional tube-to-tube fabrication impractical. Figure 4b illustrates a fabricated connection concept based on the geometric constraints of the 24-inch and 18-inch diameter column and brace members. The skewed columns and braces require significant spacing between the bolts and column face, amplifying bolt prying forces and necessitating heavy stiffener plates to maintain an adequate load path through the bolted connection. In contrast, the geometric flexibility of steel castings was utilized to taper the casting in three dimensions. This approach ensured sufficient bolt entry and tightening clearances, reduced prying forces, and enabled a compact, lightweight design that eliminated the need for extensive stiffeners and plate reinforcement.

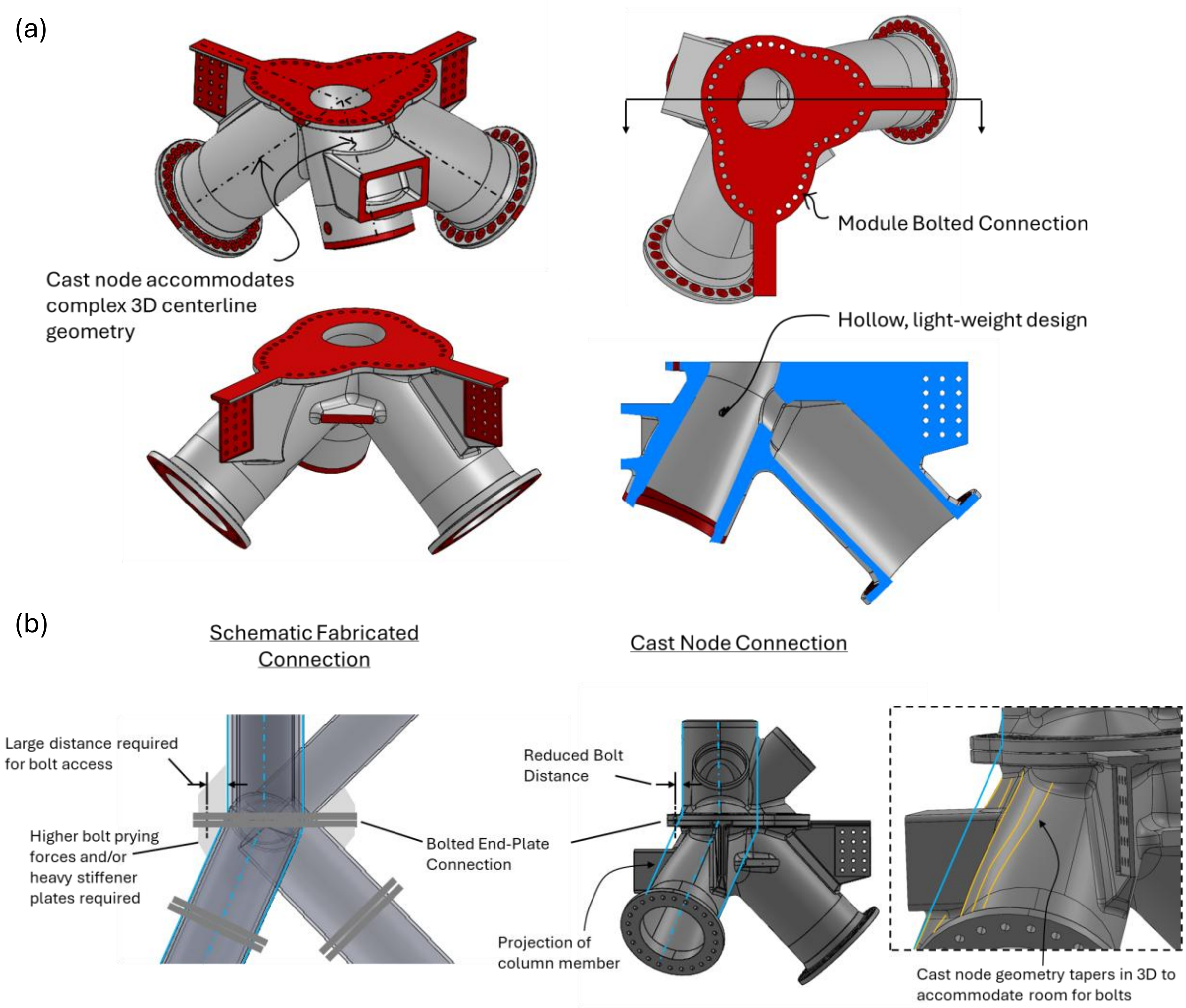


Figure 4: Level 080 Corner Node: (a) overview; (b) shaping of cast node to accommodate compact bolted connection

5.2 Level 060 Interior Node

The level 060 interior node connects eight tubular members (five 24-inch diameter pipe members via bolted end-plate connections, two 18-inch diameter pipe members via CJP welded connections, and one 10-inch diameter HSS member via lap-splice bolted connection) as shown in Figure 5. The cast node accommodates the connection between these tubular members, avoiding the use of complex overlapping TKY welds which can be challenging to design and fabricate. Besides the substantial challenges associated with welding, overlapping TKY tubular connections often suffer from inherently low connection stiffness and necessitate the use of heavy reinforcing plates, and thus the cast node approach allowed for a substantially lighter weight connection that did not require this heavy reinforcement. The substantial fatigue performance improvements over a conventionally fabricated connection for this junction should be immediately apparent.

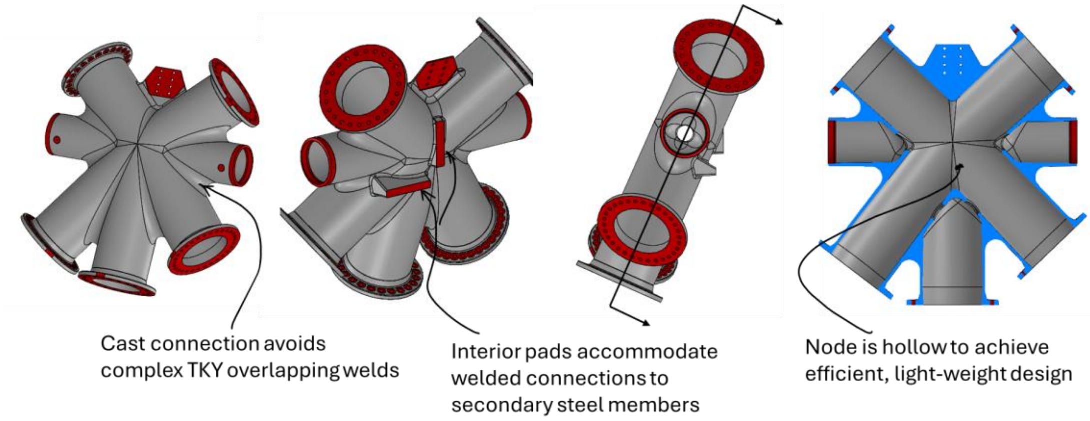


Figure 5: Level 060 Interior Node Overview

5.3 Level 030 Interior Node

The level 030 interior node connects four tubular members (via CJP welded connections and bolted flange-plate connections) and two wide-flange members (via bolted flange-plate connections). Figure 6 shows the results of a finite element analysis study that confirmed the need for internal reinforcement to achieve sufficient stiffness and strength continuity of the wide-flange member through the body of the node, which is subjected to significant flexural demands. An internal and integral "stiffener ring" feature was introduced into the casting's design to provide this local reinforcement in an efficient manner.

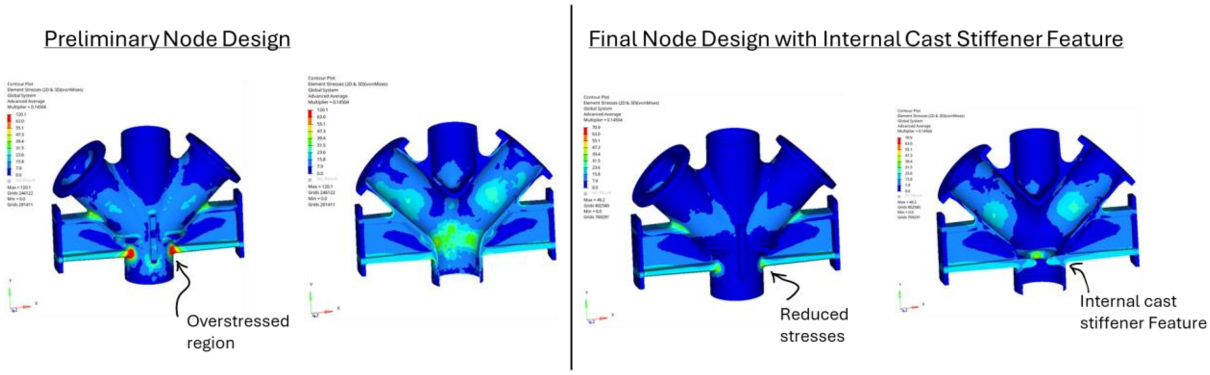


Figure 6: Level 030 Interior Node: Integral Cast Stiffener Feature for Improved Cast Node Performance

6. Cast Node Engineering Analysis

Code-based calculations were employed to confirm the adequacy of all discrete connections (bolted and welded connections) at the interface between the cast nodes and adjoining members, as per the requirements of ANSI/AISC 360 [6]. The integral bolted-end plate connections were proportioned to resist the combined axial load, bending moment, shear and torsion associated with these fixed connections and accounting for bolt prying effects. All primary tubular connections were CJP-welds which can develop the full sectional capacity of the adjoining tubular member. Other bolted and welded connections were proportioned to resist the required loading.

Finite element analysis (FEA) was leveraged to engineer and confirm the adequacy of the complex 3D geometry of the central body regions of the cast nodes. A 3D FEA model was created for each unique cast node geometry. Load sets in equilibrium were output from the global structural analysis model and applied to these local cast node FEA models. These load sets included multiple load cases, capturing a range of loading conditions from hurricane loading to launch-induced forces.

Figure 7 presents examples of a typical cast node FEA model. FEA analyses were a combination of linear elastic analyses and implicit, quasi-static, nonlinear analyses that considered nonlinear material properties. All load cases were first run as linear-elastic. Nonlinear analyses were employed to consider the worst-case load cases when material nonlinearity (as identified in FEA results exhibiting Von Mises stresses greater than the material yield stress) was observed in the linear-elastic results.

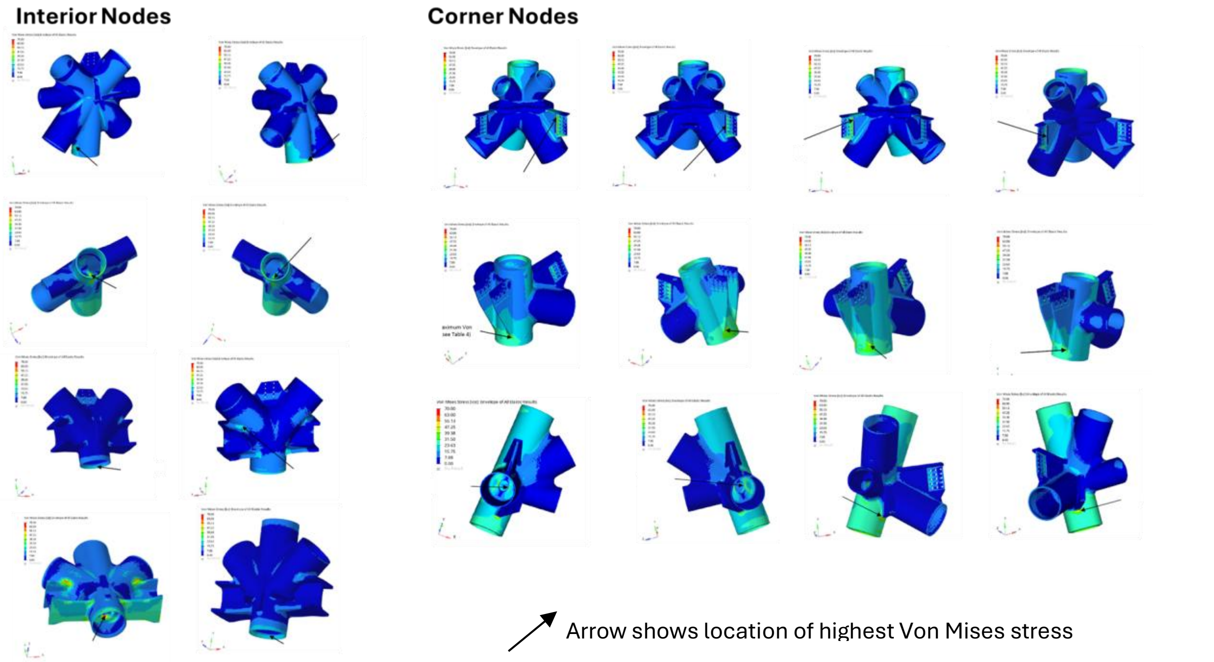
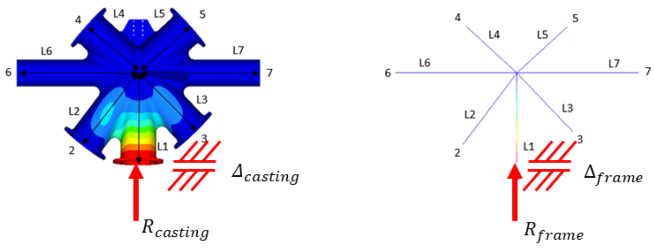


Figure 7: Cast Node Finite Element Analysis - Overview of Von Mises Stress Results

In addition to the stress analysis, stiffness studies were performed to confirm the stiffness of the cast nodes. The stiffness study was important, as many of the ML2 members were stiffness or buckling governed, and thus if optimized for strength and weight only, connection flexibility could cause excessive global structural displacements even if connection strength was adequate. Unit displacements and rotations (in all six DOFs, at each member) were applied to FEA models where each node "nozzle" was fixed in all degrees of freedom. The same displacements/ rotations were also applied to a frame analysis model with the same member extents and fixity. This frame analysis model incorporates the section sizes assumed in the global structural model. Thus, by exceeding the stiffness exhibited in the frame analysis model, it was confirmed that the cast node's design provides a stiffness that meets or exceeds the connection stiffness assumed in the structural analysis model of the overall launch tower. Figure 8 presents an example of this stiffness study for one node.



$$K_{casting} = \frac{R_{casting}}{\Delta_{casting}} > K_{frame} = \frac{R_{frame}}{\Delta_{frame}}$$

Figure 8: Stiffness confirmation of cast nodes

7. Cast Node Manufacturing

Figure 9 presents an overview of the cast node manufacturing process for the ML2 chair cast nodes, which were produced using a sand-casting process. The process begins with the creation of wooden tooling for each unique cast node geometry (Figure 9a). The tooling is CNC-cut from wood in the shape of the part. Molds are created by packing a mix of sand and an adhesive binder against the tooling, thus forming a negative impression of the final part, ready to be filled with molten steel. Steel is poured into the mold (Figure 9b), and subsequently the raw casting is processed until a near-final as-cast geometry is achieved (Figure 9c). This processing includes heat treatment to achieve the desired mechanical properties (yield stress, ultimate stress, ductility, CVN toughness, etc.) in conformance with the specified ASTM material grade. Destructive tests are performed on sample material to confirm the material properties, and a suite of non-destructive tests (radiographic testing, ultrasonic testing, magnetic particle testing, visual examination testing, and dimensional verification via 3D scanning) is performed to ensure adequately sound metal throughout the part and conformance with geometric design criteria. High-precision CNC machining at all critical touch points (bolted connections, welded connections) is performed to produce the final component, ready for shop-fabrication and field erection (Figure 9d).

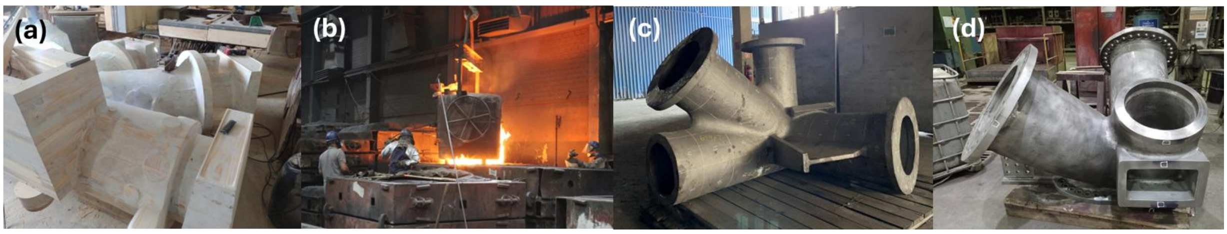


Figure 9: Cast Node Manufacturing: (a) CNC-produced wooden tooling; (b) steel poured into sand mold; (c) as-cast geometry prior to machining; (d) final cast node design incorporating precision-machined weld preparations and bolt hole patterns

Figure 10: ML2 Construction; (a) Chair field installation; (b) Module stacking showing bolted connection alignment at Level 080 cast node. Photo credit NASA Exploration Ground Systems

8. Tower Construction

Finally, the cast nodes were shop-fabricated into the various welded subassemblies described above. As shown in Figure 10a, these assemblies were field bolted to one another on-site via the bolted end-plate connections. This figure shows the completed chair structure, ready for module stacking and final ML2 field erection. Figure 10b shows the first pre-fabricated module being stacked, highlighting the alignment of the level 080 node bolted connection with the module above.

9. Conclusion

The unique structural and erection-related design requirements of ML2 necessitated an innovative approach to addressing complex, multiplanar tubular connections. As demonstrated by the connection designs in the chair portion of this launch tower, cast node technology was effectively leveraged to achieve efficient, high performance structural connections that enabled simplified shop-fabrication and tower erection.

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