A Mobile Infrastructure Engineering Consortium White Paper

How Data-Driven Structural Engineering, Best Practices, and Collaboration Can Transform Wireless Construction, Alteration, and Maintenance

OPTIMIZING WIRELESS INFRASTRUCTURE FOR COST-EFFICIENT GROWTH

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INTRODUCTION

Wireless communication infrastructure serves as the backbone of modern connectivity, enabling high-speed data and voice services globally. As demand for network expansion accelerates with 5G and early 6G deployments, mobile network operators (MNOs) and telecommunications infrastructure owners —spanning tower and building site proprietors—face the challenge of optimizing capital expenditures (CAPEX) and operational expenses (OPEX) while scaling their networks cost-effectively, and with minimum delays. Historically, rapid industry expansion and the urgent need for coverage have led these stakeholders to rely on inefficient and fragmented processes and data systems, inconsistent documentation, and reliance on disparate engineering methods.

To help sustain profitable growth, the industry needs to shift towards tightly integrating structural engineering best practices with data-driven engineering approaches that leverage advanced software, structural analysis with precise physical asset data, and continued adoption of emerging technologies. This transformation is critical for streamlining site development, reducing deployment timeframes, and improving long-term infrastructure reliability. Structural engineering methodologies that leverage comprehensive digital representations of physical assets, help stakeholders reduce unnecessary fieldwork, enhance asset utilization, and maximize cost efficiency.

Recognizing the need for standardized engineering practices to drive quality and efficiency, leading telecommunications engineering firms—including Colliers Engineering & Design, Congruex, Kimley-Horn, and Paul J. Ford & Company—have formed the Mobile Infrastructure Engineering Consortium (MIEC). Optimizing project workflows, which are highly manual across most of today's telecommunications infrastructure deployments, is a key focus area for the Mobile Infrastructure Engineering Consortium. Through their collaborative efforts, the MIEC has demonstrated the effectiveness of this industry paradigm shift, achieving documented cost savings exceeding $700 million across 90,000 5G wireless infrastructure projects in the U.S. By applying key learnings from MIEC, along with standards and regulations compliance as outlined by the Telecommunication Industry Foundation (TIF), there is great potential for similar economic benefits to be realized globally as 5G and 6G networks continue expanding.

This white paper explores how telecommunications companies can optimize structural engineering practices, adopt standardized workflows, and leverage emerging technologies such as Artificial Intelligence (AI), Machine Learning (ML), and Augmented Reality (AR). These innovations will enhance structural integrity, reduce inefficiencies, and ensure that networks are built safely and for long-term scalability and resilience.

1. Market Analysis – The Economic Impact of Telecommunications Infrastructure Engineering

The telecommunications industry is undergoing rapid transformation, driven by continued growth in demand for advanced wireless services and the associated network expansion to meet demand. As network densification increases, so does the need for structural engineering expertise to ensure the reliability and safety of new and existing infrastructure. Structural analysis is required whenever new equipment is added or modified to confirm that towers, mounts, and supporting structures can handle increased loads and environmental forces. Without proper analysis, telecommunications companies risk structural failures, regulatory non-compliance, and increased operational costs.

1.1 Structural Engineering Cost Considerations:

Structural engineering costs vary and are embedded in the overall expenses for building and maintaining telecommunications infrastructure. Many factors contribute to the variability of these costs, including regional regulatory requirements, geographic and climate conditions, the condition or age of existing structures requiring modification, and other unique circumstances. Considering global 5G infrastructure investment was estimated at USD 16.69 billion in 2023 with an anticipated CAGR of 22.9% from 2024 to 2030 [1], optimizing structural engineering processes and taking advantage of opportunities to drive cost efficiencies at scale is critical.

The primary cost drivers for structural engineering include:

- **Structural engineering design for new site construction:** New site construction requires comprehensive structural engineering design to ensure the infrastructure meets operational and regulatory standards. Regional building codes and standards significantly impact design and cost, as well as factors such as wind loads, seismic activity, and future equipment scalability.
- **Structural analysis for existing infrastructure/site modifications:** Structural analysis is required whenever any equipment is added or modified on an existing structure to assess load capacity, environmental stress factors, and potential reinforcements. This process is essential for extending the lifespan of existing infrastructure while ensuring compliance with standards and safety regulations.
- **Mount analysis for new equipment installation or site modifications:** Mount analysis involves evaluating the demand/capacity of the mounts attached to the macro structure to accommodate new or modified equipment. This includes assessing static and dynamic loads introduced by antennas, radios, cables, and environmental factors like wind and ice accumulation. Mount analysis is crucial for

preventing structural failures, particularly as wireless networks evolve and the equipment increases in size and quantity. It is also essential that the mount analysis addresses the mount-to-tower interaction to ensure that the design loads for the mount do not adversely affect the tower.

- **Structural reinforcement where necessary:** When analysis determines that an existing structure cannot support additional loads, reinforcement solutions such as bracing, anchor upgrades, replacing fatigued materials, or foundation modifications may be required. These activities ensure that structures can safely support evolving network demands, particularly in regions with stringent environmental or seismic requirements.

By applying best practices and leveraging precise, up-to-date data, MNOs and tower companies can reduce unnecessary reinforcements, streamline engineering processes, and improve asset longevity, driving significant cost savings.

1.2 Economic Implications for MNOs

Telecommunication structures supporting mounts and equipment are frequently exposed to changing equipment demands. Any change in equipment, scale, or geometry of the structure or the structure's principal purpose that results in a 5% change in demand-capacity ratio is referred to as a "Changed Condition" as defined by the ANSI/TIA-222-H [2]. Structural analysis is required (per many standards) for any equipment addition or modification that creates a significant changed condition and can represent a significant share of structural engineering expenditures. MNOs must prioritize structural engineering investments to balance network expansion, cost efficiency, and regulatory compliance. Structural assessments are essential for ensuring long-term asset performance and risk mitigation, particularly as networks evolve to accommodate new technologies, spectrum bands, and higher antenna loads. By conducting these assessments efficiently with optimized engineering workflows that leverage persistent and accurate site data, MNOs can achieve:

- **CAPEX Savings**: Avoiding unnecessary structural modifications and minimizing material costs.
- **OPEX Reductions**: Predictive maintenance and site monitoring reduce the need for frequent field inspections.
- **Risk Mitigation**: Preventing structural failures that could lead to service disruptions, financial liability, and regulatory penalties.

1.3 Engineering Standards and Global Implications:

Structural engineering requirements and best practices differ by region based on climatic conditions, regulatory environments, and infrastructure requirements. Below is a summary of some of the key regional standards and their differing focus areas [3]. A deeper analysis regarding the impacts various standards have on structural engineering is provided in section 4:

- ANSI/TIA-222 (United States) – Focuses on wind, ice, and seismic resilience.
- Eurocode 3 (Europe) – Prioritizes fatigue analysis and cross-border standardization.
- GB 50135 (China) – Balances cost-efficient methods with extreme weather considerations.
- IS 875 & IS 802 (India) – Emphasizes cyclone resistance and lightweight materials.
- AIJ Standards (Japan) – Specializes in seismic resilience and corrosion protection.
- CSA S37 (Canada) – Similar to ANSI/TIA-222, it addresses wind, ice, seismic loading, material requirements, and foundation requirements.

Harmonizing engineering standards and adopting best practices from ANSI/TIA-222 globally can improve efficiency, cost management, and safety. MIEC has demonstrated that standardizing structural analysis methodologies and centralizing data management can help MNOs accelerate deployment timelines and reduce costs while maintaining compliance and network reliability.

1.4 Summary: The Financial and Operational Benefits of Engineering Best Practices:

Proactive engineering investment and the adoption of advanced structural analysis methodologies will be essential for MNOs and telecommunications infrastructure owners to ensure resilient, cost-effective infrastructure worldwide. By implementing best practices, leveraging accurate data, and adopting advanced engineering tools, telecommunications companies can:

- **Reduce CAPEX and OPEX** through more efficient resource allocation.
- **Improve network reliability** by ensuring structural integrity across all deployment scenarios.
- **Enhance operational efficiency** with standardized engineering workflows and digital tools.
- **Minimize regulatory and legal risks** by adhering to industry standards.

This proactive approach will enable the most cost-effective and efficient migration to 6G. By optimizing structural analyses at scale, MNOs can accelerate deployment timelines and revenue generation and reduce long-term liability and risk, setting a strong foundation for future network advancements.

2. Structural Engineering Fundamentals

Structural engineering is critical in maintaining telecommunications infrastructure's integrity, performance, and code compliance. This section outlines the primary engineering activities associated with telecommunications infrastructure, the expertise and resources required to execute these tasks, and the typical configurations encountered in the field. Additionally, it explores lifecycle considerations, complexities of engineering practices, and the critical role of engineers as faithful agents to their clients.

2.1. Typical Telecommunications Structures and Configurations

A large majority of wireless telecommunications equipment is located on what is referred to as macro structures, with the most common being monopoles, self-support, and guyed towers. However, due to required network densification in urban areas with little to no green space, wireless telecommunications equipment is increasingly deployed on non-traditional structures like rooftops, water tanks, transmission towers, light poles, and billboards. Due to each structure's unique characteristics, these applications often require custom engineering approaches. For example, rooftop installations may involve more complex analysis to meet code compliance while accounting for complex load paths and material constraints.

Telecommunications mounts are available in the following different configurations, each with unique engineering challenges and requirements:

- **T-Arm Mounts:** T-arm mounts are straightforward configurations typically installed on poles or other low-profile structures. Their simplicity offers easy maintenance and installation, but they require careful analysis to ensure stability under varying load conditions.
- **Sector Frames**
  - **V-Frames**: These provide robust support for multiple antennas and their supporting equipment and are typically designed for balanced load distribution.
  - **T-Frames**: T-frames are similar to V-Frames but are designed for lighter, smaller antenna loads and have different load path considerations, often requiring precise structural mapping and analysis when larger, heavier loads are installed.
- **Platform Mounts:** These mounts accommodate equipment configurations like those of T-arms but also include design elements that provide ease of access

and additional stability for the installation. They often introduce complexities in load distribution and interaction with the underlying tower structure due to their ability to typically support larger loading configurations than T-arms.

- **Non-penetrating ballast mount:** A mounting system that resists sliding and overturning moment entirely from the self-weight of its structural members, appurtenances, and mounting pipes. It is supplemented by adding weight to the attached mounting trays with ballast. Types of non-penetrating mounts include ballasted rectangular sleds and tripod mounts.[1]
- **Penetrating/anchored mount:** A mounting system positively attached to the underlying structure via weld, mechanical, or adhesive anchor. Its stability is derived through load transfer from anchored connections to the roof framing system or other building components. [1]

2.2 Engineering Activities and Required Expertise

The engineering tasks related to telecommunications infrastructure are diverse and demand specialized knowledge and collaboration:

- **Structural Mapping and Inspections:** Structural mapping involves fieldwork by competent and qualified personnel who gather critical data on the structure's geometry, components, and loading conditions. Collaboration with the Engineer of Record (EOR) is essential to define the scope of work (SOW) and collect relevant information for accurate analysis and design. After the initial mapping of a site is completed, continued mapping should never be required with proper data management and strict adherence to completing Post-Installation/Post-Modification inspections (PII/PMI), as detailed in section 3.
- **Structural Analysis:** Structural analysis performed by the EOR ensures code compliance per ANSI/TIA-222 and other applicable standards. The level of rigor depends on the site's specific requirements, the Authority Having Jurisdiction (AHJ), and the client's needs. An effective EOR will balance compliance and practicality, educating when the AHJ's requirements are not in sync with the structure's codes, regulations, and intended use.
- **Structural Modification Design:** Designing modifications requires an EOR knowledgeable in ANSI/TIA-222 (or applicable) standards and focused on constructability (tower fit-up, site accessibility, climbing facility, safety climb considerations, lighting, and marking, etc.). The goal is to avoid custom designs whenever possible, leveraging standardized solutions to reduce costs and improve efficiency. Engineers must consider factors like customer needs, retrofit capacity, future network upgrades, and the physical capabilities of installation crews. A competent EOR will act as a faithful agent to their client and balance the need to reduce cost with meeting installation and 'on-air' timelines.

- **Construction Drawings**: These drawings, prepared by the EOR, depict the overall site layout, equipment type and placement, and structural modifications. Consistency between equipment layout and structural deliverables is crucial. Construction drawings should clearly depict the overall site scope of work to the General Contractor (GC) and account for safety climbs, structural modifications, and other essential elements to facilitate efficient construction processes. [2] A well-designed construction drawing set should incorporate and reference any guidance from the structural analysis or structural modification design so that the GC can effectively plan and perform work from a single source of information.

2.3 Lifecycle and Ecosystem of Engineering Activities

Engineering activities are inherently interconnected and influenced by lifecycle considerations:

- **Engineering Workflows**: When an MNO upgrades or changes equipment in the United States, the International Building Code (IBC) is the primary model code that mandates structural analysis of both the mount and the macro structure. The IBC is also often used as a benchmark for international projects. Still, hybrid model codes exist in various countries where local governments may modify IBC for regional seismic, wind, and load conditions. Accurate data on structural components, geometry, and loading configurations is critical. Missing information often necessitates a field mapping exercise to gather data. The workflow typically includes the following steps:
    - Application submission by the end user’s RF engineer detailing proposed loading configurations.
    - Field and/or structural mapping to gather the most up-to-date data.
    - Structural analysis of mounts and macro structure by the EOR.
    - Development of construction drawings.
    - Post-installation/post-modification inspections (PII/PMI) to verify compliance and close the loop on any assumptions made during analysis and design.
- **Workflow Variations:** Some end users prefer to complete mount engineering activities before generating preliminary construction drawings, while others reverse the sequence. Awareness of these variations and their downstream impacts is critical for all stakeholders.

2.4 Engineering Complexities and Variances

Engineering practices in structural analysis are nuanced, and minor differences in approach can yield drastically different results. It is imperative that MNOs properly vet the professionals they are engaging in for these services. This includes, but is not limited to, making sure they are familiar with and able to apply the required standards accurately. They are committed to effectively balancing code compliance and leveraging economic solutions as allowed by the standards (Computational Fluid Dynamics, changed condition, etc.).

- **The Role of the Faithful Agent**: A skilled EOR balances the delivery of quality and code-compliant solutions that consider the financial impacts to the client to provide the most economical and viable outcomes. Understanding the intended use of the structures and the client's underlying needs, such as the preference to modify versus replace mounts or aerial welding versus bolted solutions, is paramount. The EOR must also account for additional items as defined by the client, which may include lease space requirements, optimization of equipment loads using CFD and wind tunnel testing, changed condition assessments, and network performance considerations.

- **Engineering that Reflects Real-World Application**: Varying assumptions or engineering methodologies can significantly impact analysis outcomes. For example, assumptions about loading conditions or material properties might lead to divergent recommendations on required structural modifications. In a case study conducted in the TIF White Paper Titled "Mount Analysis: Recommended Best Practices," the various potential combinations of mount structural modeling criteria alone can result in more than 1e+40 (duodecillion) different combinations of criteria possible, which, with non-consistent engineering practices, can drive significant variance in engineering results that can result in compromising both safety and reliability of the network. This often drives operational costs higher for the MNO and even leads to loss of revenue in cases where network coverage is degraded or lost.

- **Code Compliance and Risk Management:** Selecting the appropriate code and risk category is essential to meeting the structure's intended use [3] [4]. Misaligned engineering assumptions, such as applying an overly conservative risk category or utilizing incorrect standards based on the structure's primary intended use, can unnecessarily inflate costs.

2.5 Case Studies

An effective data management program proves that the engineers engaged provide more efficient and effective solutions that decrease installation costs and failures.

Case Study 1: Understanding Structural Overstresses vs. Network Performance Requirements

An MNO proposed upgrading equipment installed on T-arms supported on a faux palm tree. The mount analysis EOR delivered a 'failing' analysis due to a lack of data regarding the mount's ability to prevent the mount from 'rotating' when experiencing wind events (see sketch below). Due to the constraints of the faux palm tree and AHJ requirements to maintain stealthing, there were very few economical or reasonable options to retrofit or replace the existing T-arms.

Figure 1. Illustration of typical rotational concerns for T-arm installations

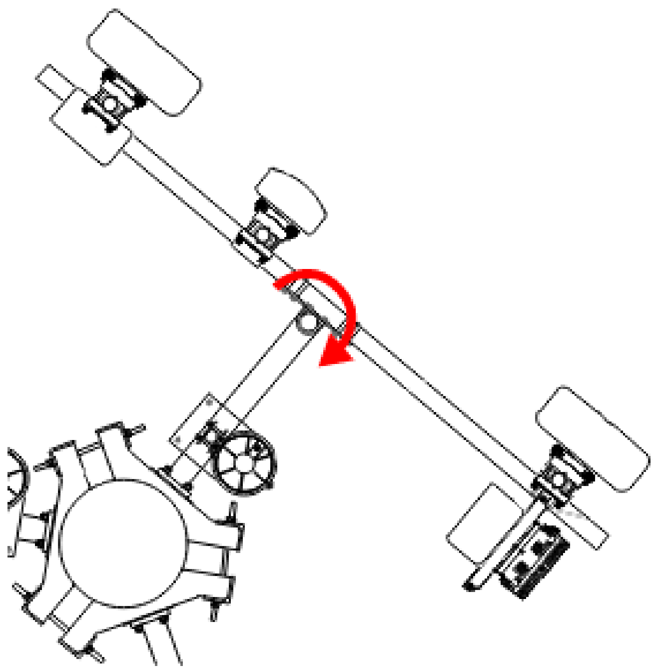


Figure 2. Image of T-arms installed on a faux palm tree

After further discussion with the MNO, it was determined that while no 'calculable' data existed to confirm rotation would not occur, the site had been on-air for over a decade with no reported rotation issues. Additionally, the MNO confirmed that there was redundant coverage in the network and that the site was under an ANSI/TIA-222 required maintenance and condition assessment program. The MNO was comfortable with the assumed risk of possible rotation in the mount, knowing that various measures were in place to ensure coverage to the impacted surroundings.

The EOR revised their analysis to a 'passing' result with language confirming that the MNO was aware that any rotation that may occur was not due to an overstress of the steel members. Instead, in the unlikely event that rotation did occur, it would be considered a serviceability issue and would be addressed via routine maintenance and ongoing inspection monitoring of the site.

Case Study 2: Optimizing Mount Capacities Through CFD Usage

Preliminary results of a mount analysis on a platform mount showed various overstresses in the mount steel members. With limited vertical real estate on the tower, the only viable solution was to replace the mount, incurring significant costs and time delays to the project.

After further evaluation, the EOR noted that the MNO had CFD data on file for several of the proposed antennas. When the mount was re-evaluated with the reduced wind loads made possible by the more accurate and correct CFD values, the analysis showed that the platform mount was adequate to support all proposed loading. This resulted in significant cost and time savings for the MNO.

Case Study 3: Proper Analysis of Non-traditional Structural Materials

An EOR delivered a mount analysis to an MNO showing that an existing rooftop concealment structure, constructed of Fiber-reinforced Polymer (FRP) materials, was overstressed and required significant remediations and retrofits before installing new equipment. A 3rd party review by the MNO's consulting engineer noted that the EOR performed analysis checks of the FRP materials using traditional steel material checks. When updated to the correct formulas and considerations for FRP, as allowed by code, the analysis provided a passing result. It allowed the MNO to proceed directly to the installation of the proposed equipment.

Figure 3. Image of a typical rooftop FRP concealment frame

Case Study 4: Understanding the Actual Impact of a Loading Change to a Structure

As part of their network upgrade plan, an MNO proposed the removal of legacy equipment alongside the installation of proposed equipment on an existing water tower. At the time of the project kickoff, there was no structural documentation regarding the supporting water tower. However, the MNO confirmed with the tank owner that the tank was routinely inspected and maintained per all required codes and standards.

The MNO was advised that a full structural mapping of the antenna mount, tank, and its foundations and an up-to-date geotechnical investigation were required to proceed with structural analysis services. These investigative services would incur significant costs and delays to the project.

The MNO's consulting engineer noted that when compared to the as-is state of the tank, the MNO's final loading configuration would result in a net decrease in loading on the tank. As such, the applicable building codes could be leveraged to demonstrate that the condition and reliability of the overall structure would be an improvement from the current condition. As such, no structural evaluation would be required. It should be noted that this was contingent upon the routine inspection and maintenance of the tank in compliance with all applicable codes and standards.

Figure 4. Image of antennas installed on a water tank catwalk

2.6 Summary

Structural engineering for wireless telecommunications infrastructure encompasses a broad spectrum of activities requiring specialized expertise and careful coordination. By understanding the nuances of typical structure configurations, the intricacies of engineering practices, and the complexities of lifecycle interactions, MNOs, and engineers can optimize structural performance and ensure compliance while managing costs effectively.

3. International Standards Governing Structural Analysis

Structural engineering standards are essential for ensuring wireless infrastructure's safety, performance, and durability. These standards provide guidelines for designing, analyzing, and maintaining diverse installations, including tower structures, on-building setups, water tower sites, and mounts for deploying antennas and other equipment. This section explores the international standards that govern these practices, the critical role of the Telecommunications Industry Association (TIA) in the United States, and the potential for TIA methodologies to inform global improvements. Examining these standards highlights opportunities to enhance structural resilience and operational efficiency worldwide.

3.1 Key International Standards

International structural standards vary significantly based on regional priorities, climatic conditions, and regulatory frameworks. Each standard reflects the unique challenges faced by its implementing region. The alignment and unification of various standards across international boundaries would benefit MNOs and telecommunications infrastructure owners to promote safer, more efficient, and more cost-effective mobile infrastructure deployments.

In the United States **ANSI/TIA-222**, "Structural Standard for Antenna Supporting Structures, Antennas and Small Wind Turbine Support Structures", is a comprehensive guideline for ensuring structural reliability under diverse conditions. The development process is industry-driven, led by the professionals doing the work, and is open to all companies and individuals wishing to participate. This standard emphasizes rigorous wind, ice, seismic, and fatigue considerations critical for infrastructure in all geographic locations, including topographically influenced, hurricane-prone, and earthquake-sensitive areas. Further, ANSI/TIA-222 is adopted by the International Building Code (IBC) and requires robust inspections to identify potential areas of non-compliance within infrastructure due to aging and use. These provisions have ensured the long-term reliability [1] of communication towers in challenging environments such as the Gulf Coast, where hurricanes are frequent; the Northern Plain, where multiple inches of radial ice can accumulate on tower steel; and in California, where earthquakes can occur.

In Europe, **Eurocode 3** focuses on harmonizing structural standards across member countries. It prioritizes ultimate limit state design and fatigue considerations to address variable load impacts over time and incorporates biodiversity and aesthetic considerations. Urban installations, such as rooftop antenna setups in historic city centers, benefit from these environmental integrations, ensuring functionality and minimal ecological disruption.

China's **GB 50135** standard emphasizes cost-effective solutions for large-scale deployments. This approach addresses the need for rapid expansion while ensuring resilience against extreme weather events like typhoons. Much like the U.S. experience with ANSI/TIA-222 in coastal regions, implementing GB 50135 has enabled the development of high-capacity networks that withstand severe storms.

In India, **IS 875 and IS 802** focus on utilizing cyclone resistance and lightweight materials for cost-sensitive projects. These standards ensure infrastructure safety in regions prone to monsoons and cyclones, particularly along the coastal belt.

Japan's **AIJ Standards** excel in addressing seismic resilience, a necessity in one of the world's most earthquake-prone nations. These standards also emphasize corrosion resistance, which is vital for coastal installations. The precision of these guidelines mirrors TIA's commitment to durability and adaptability in adverse conditions.

The **Canadian Standards Association CSA S37** governs the structural design and safety of telecommunications towers and antenna-supporting structures in Canada. While CSA S37 shares similarities with ANSI/TIA-222, differences exist due to variations in climate conditions, regulatory frameworks, material specifications, and structural analysis methodologies. CSA S37 is designed for the more extreme Canadian Climate with higher wind, ice, and seismic design requirements.

In Australia and New Zealand, AS 3995-1994 is commonly used for structural assessment and engineering of telecom towers, often supplemented by **AS/NZS 1170** for structural and load calculations. Like ANSI/TIA-222, the AS/NZS 1170 standard provides comprehensive guidelines on how to calculate and apply environmental loads, particularly wind loads.

3.2 Role of TIA Standards in the USA

The **ANSI/TIA-222** standard has set a high benchmark for structural analysis in the wireless infrastructure sector. ANSI/TIA-222 combines safety, performance, and technological innovation to address diverse challenges while avoiding unnecessary costs to ensure the structure's performance. This standard has been in practice for over 60 years and has evolved to reflect the real-world behavior of telecommunications structures more accurately.

By incorporating comprehensive wind, ice, and seismic and fatigue design considerations, ANSI/TIA-222 ensures structural integrity, even in high-risk areas, without undue cost burdens. For instance, communication towers in Florida, designed to meet ANSI/TIA-222 criteria, have withstood major hurricanes, providing critical connectivity during disasters. Additionally, ANSI/TIA-222's emphasis on maintenance protocols directly impacts the longevity of these structures.

TIA members work within Engineering Committees to produce industry-leading standards for installing, maintaining, and testing telecommunications products and technologies. These standards apply to a variety of products, including cellular systems, fiber optics, emergency communications, and data centers, in a very fair, one-company, one-vote environment that focuses on solving technical issues practically and impartially. TIA's TR-14 is uniquely focused on the antenna structures needed for wireless communications and backhaul. This community is an unparalleled resource to the industry with its deep practical experience and technical expertise.

3.3 Global Benefits of Adopting TIA Standards

The global wireless industry stands to gain significantly from adopting some or all ANSI/TIA-222 principles. Enhanced safety is one of the most immediate benefits. In regions with frequent extreme weather, such as Southeast Asia, incorporating ANSI/TIA-222's rigorous wind analysis protocols could reduce structural failures and improve public safety. For example, there have been numerous instances of tower collapses over the past several years in the typhoon-prone regions of the Philippines, Taiwan, China, and Vietnam due to lack of reinforcement, poor design, and insufficient maintenance. Modern standards like ANSI/TIA-222-H have introduced stricter wind and load conditions to help mitigate these vulnerabilities.

Efficiency is another key advantage. ANSI/TIA-222's streamlined engineering workflows, supported by digital tools, reduce repetitive analyses and expedite deployment timelines. This approach was evident during the rollout of 5G infrastructure in the U.S., where standardized practices enabled rapid network expansion while minimizing costs.

Reliability improvements stem from TIA's focus on consistent data retention and management. By maintaining accurate structural records, operators can avoid unnecessary rework and ensure long-term planning. Equipment manufacturers also benefit from the evolution of consistent and standardized designs that ensure their products and materials are efficiently produced and are readily available to meet market demand. This methodology is particularly relevant for emerging markets where infrastructure expansion often outpaces regulatory frameworks.

3.4 Comparison and Gaps in International Standards

Despite these benefits, significant gaps exist between ANSI/TIA-222 and many international standards. For instance, while TIA outlines the requirements for maintenance and condition assessment programs, some regions lack similar requirements, leading to undetected structural deterioration. Additionally, the U.S. emphasis on wind and seismic resilience is often underrepresented in global frameworks. It should also be recognized that the U.S. tower market has been developed to facilitate the co-location of multiple MNOs on each structure. This has forced the standards to evolve not just for new structures but to allow for the maximum safe utilization of a structure for multiple MNOs through modification. This reduces the number of structures by allowing this co-location.

Aligning international standards with ANSI/TIA-222 could address these discrepancies or enhance cost efficiencies. For example, regions vulnerable to hurricanes or earthquakes, such as Southeast Asia and parts of South America, could benefit from adopting TIA's rigorous design criteria to enhance infrastructure resilience as highlighted in the case studies below and as implemented across the European region with the Eurocode standards.

3.5 Case Studies

The Caribbean's adaptation of ANSI/TIA-222 provides a compelling success story. Several nations, including Trinidad and Tobago and Puerto Rico, incorporated TIA methodologies after experiencing significant tower failures during hurricanes Irma and Maria in 2017 [2], resulting in improved structural performance and reduced downtime. Similarly, in South Asia, TIA-inspired training programs have equipped local engineers with the expertise to implement advanced structural solutions. However, challenges persist in regions with limited regulatory oversight. For example, in parts of Africa, the absence of routine inspections and consistent engineering practices has led to frequent failures [3]. These examples underscore the need for broader adoption of TIA's comprehensive framework.

3.6 Call to Action for Global Harmonization

Standardizing structural analysis practices worldwide offers numerous benefits. By adopting ANSI/TIA-222, nations can ensure safer and more reliable infrastructure, reduce costs, and streamline deployment processes. A collaborative approach involving international bodies, regional governments, and industry stakeholders is essential to achieve this goal.

Pilot programs in regions with minimal standards can demonstrate the tangible benefits of adopting TIA principles. For example, implementing TIA-based designs in typhoon-prone areas could showcase improved resilience and longevity in a structure, encouraging wider adoption.

3.7 Conclusion

Structural standards are the foundation of safe and efficient wireless infrastructure. The U.S. experience, exemplified by ANSI/TIA-222, offers a valuable model for addressing global challenges. By embracing proven methodologies, the global wireless industry can enhance resilience, reduce costs, and achieve greater interoperability. Collaboration and commitment to standardization are vital to realizing these benefits and ensuring a more connected future.

4. Perspective on Structural Engineering for Wireless Infrastructure

Structural engineering has become increasingly vital in telecommunications, particularly for MNOs' infrastructure buildouts. While mount analysis has always been possible, the rise of 5G/6G deployments—adding more equipment to mounts—has made it essential. Engineers must now evaluate mounts to ensure they are structurally designed to handle the required loads. This section explores four business models tied to required structural mount analyses that MNOs have historically employed in the United States. These different approaches provide valuable insight regarding which best practices can be considered globally. By examining the benefits and considerations of these models, with a particular emphasis on best practices, data control, and cost efficiencies, MNOs can implement consistent structural engineering processes, enabling them to drive operational efficiencies, achieve significant cost savings, and make informed decisions that balance immediate needs with long-term benefits. As mentioned earlier, the Mobile Infrastructure Engineering Consortium has documented over USD 700 million in savings across 90,000 MNO projects in the U.S. by establishing consistent engineering best practices and leveraging precise data management capabilities. The different business models employed by MNOs for Mount Structural Engineering are detailed below.

4.1 Model 1: MNO-Controlled Mount Asset

In this model, the MNO considers the mount as its asset, retaining complete control over the associated data and ensuring strict adherence to established engineering standards. The approach relies on a carefully managed framework involving a fixed number of pre-qualified vendors to maintain consistency and accountability over a high volume of deployments.

Controlled vendor management is fundamental to this model, where the MNO works with a limited number of properly vetted vendors to reduce complexity and ensure quality. Managing fewer vendors allows for greater consistency in deliverables, accountability, and streamlined communication. In addition, engineers of record (EORs) are given significant authority and responsibility to provide cost-effective solutions and maintain data on structural conditions and live loading. These engineers act as faithful agents of the MNO, delivering code-compliant and economical designs.

Establishing effective communication and accountability measures is also critical in this model. By eliminating communication barriers between engineers and contractors, MNOs can foster greater collaboration and ensure that deployment projects are managed efficiently and implemented as designed. The MNO also establishes a third-party engineering review program to ensure quality control and to identify potential excessive costs resulting from inaccurate and over-engineered solutions.

Benefits: The primary advantage of this model lies in its potential for long-term cost reduction. MNOs can avoid redundant expenses and streamline workflows by eliminating third-party markups and maintaining detailed structural engineering data collected through Post-Modification Inspections (PMIs), enabling live models that reflect in-field conditions. Direct engagement between the MNOs and EORs reduces the likelihood of conflicts of interest, ensuring that engineering solutions prioritize quality and efficiency. Additionally, comprehensive data retention eliminates repetitive and costly site mapping while facilitating the creation of functional digital twins, enabling advanced planning, innovative engineering solutions, and rapid disaster recovery. Furthermore, direct communication pathways between engineers and contractors enhance collaboration and improve project outcomes.

Considerations: While this model offers robust control and significant potential cost savings, it demands dedicated management resources from the MNO. Tracking mechanisms and staffing must be in place to handle the oversight requirements and additional workflow tasks associated with the PMI processes. This model's success hinges on the MNO's ability to maintain consistent vendor management and ensure the application of engineering standards. Without careful planning and sustained oversight, the benefits of this approach may diminish over time.

4.2 Model 2: Third-Party Control of Mount Data

Under this approach, the MNO relinquishes the management of mounts as an asset and delegates control of mount data and associated engineering processes to third-party turnkey firms. These firms manage the entire workflow, often subcontracting to a wide range of engineering vendors. For large U.S. MNOs, this approach can result in more than 400 different EORs providing engineering services, leading to inconsistencies, inefficiencies, and quality issues. This hands-off approach minimizes the MNO's direct involvement in day-to-day construction and deployment operations, but there are consequences with MNOs incurring higher costs and increasing risk.

Benefits: Third-party control simplifies the assignment of engineering tasks for MNOs, allowing them to focus on their core business operations. The reduction in management burden can free up resources and expenditures for other strategic priorities.

Considerations: While seemingly efficient at first glance, this model introduces several inefficiencies and risks. Contractors often face significant challenges due to insufficient guidance when constructability issues arise. Without consistent collaboration from an EOR, they frequently rely on their own processes to resolve issues that consume additional time and resources, resulting in inconsistencies across the network and potential long-term quality issues. Similarly, equipment manufacturers receive little to no feedback from contractors on product performance, limiting their ability to improve offerings and align them with MNO's operational requirements.

Additional challenges can also emerge when structural scope determinations are made by site acquisition personnel or representatives without the necessary engineering expertise that an EOR would provide. This can lead to unnecessary services being ordered, such as structural mapping and analysis for "no-change" conditions. Third-party turnkey firms, although convenient, often prioritize their financial interests over the MNOs, creating conflicts of interest. These firms may favor recommendations that increase their deliverable volumes, such as replacing mounts rather than modifying them, or may not emphasize engineering quality and code compliance, which is ultimately more costly to the MNO. Without a third-party engineering review program in place to identify these issues, the MNO unknowingly incurs these unnecessary and excessive costs.

As evident with third-party control, the absence of a PMI process compromises quality and accountability for the engineer and contractor to install an effective solution, leading to increased project durations, additional spending by the MNO on subsequent projects, and increased risk. During the more than 20,000 PMIs completed by the MIEC, installation fault is the most common reason for a failing PMI deliverable. As depicted in the video produced by TIF & NATE titled "How Compliance with the ANSI/TIA-222, ANSI/TIA-322, ANSI/ASSP A10.48, and TIA-5053 Standards Set up Contractors for Success", the term installation fault means that the install did not properly occur. It is intended to show a problem with the installation that may have been due to design, communication, lack of support, and other issues. It is never intended to place fault solely on the Engineer, Contractor, Manufacturer, Tower Owner, or MNO.

Without a PMI process for every site installation, the MIEC has found that an MNO is likely to have quality failures and adverse situations in the field as often as 40% of the time across all sites. **Several examples of these are illustrated and detailed in Appendix B.**

Another common occurrence is that proposed mount replacements were not completed, yet the proposed equipment was installed, leaving an existing condition that is not code-compliant. In some cases, the existing mount has been replaced with a new mount, but it is different than what was specified. While mounts may seem "equivalent" to those lacking engineering expertise, nuances in steel geometry and member sizes will yield drastically different structural capacities. In addition, changes in the weight and area of the steel frame may induce additional stresses on the underlying structure that were not accounted for.

Furthermore, accurate data of in-field conditions cannot be preserved without a robust PMI process or centralized data management and retention strategy, which leads to site mapping becoming a recurring expense. This lack of continuity means that engineering firms often require full fees for repeated services, resulting in perpetual costs. Unfortunately, many MNOs are not enforcing PMIs in conjunction with their infrastructure deployments. These MNOs remain unaware of the additional costs, inefficiencies, and quality issues caused by the lack of a PMI process, a data gap, fragmented engineering workflows, and their limited control over projects.

Finally, the lack of interpretive data tools limits the MNO's ability to leverage historical data for future network planning. This oversight diminishes long-term operational efficiency and increases dependency on repetitive engineering services. Delays in deliverables further compound inefficiencies eroding the perceived simplicity of this approach.

4.3 Model 3: Hybrid Approach - MNOs

This model blends elements of the first two approaches. The MNO retains ownership of the mount asset but delegates its management to third-party firms. While an engineering standard is in place, enforcement and accountability mechanisms are limited, resulting in inconsistencies.

Benefits: The hybrid approach offers a balance between operational simplicity and control. Engineering tasks can be easily assigned to third-party firms, reducing the MNO's management burden compared to Model 1. This model is particularly useful for MNOs that lack the resources to oversee every aspect of mount data management.

Considerations: Although the MNO retains ownership of the mount, its passive role in data management still introduces inefficiencies. Like in the Model 2 approach, contractors frequently face constructability challenges without adequate EOR support, and feedback loop limitations inhibit manufacturers from gaining input necessary to improve their products, which could help the MNO enhance overall efficiency. The lack of data management and comprehensive PMI processes under this model remains an issue, leading to inconsistent site mapping, recurring expenses, and inefficiencies. Engineering services, often subcontracted by third-party firms, vary widely in quality and cost, as deliverables depend on the practices of individual vendors rather than a unified standard. These inefficiencies can drive up costs significantly over time.

Under this model, minimal oversight also creates accountability and quality control vulnerabilities. Deliverables from engineering firms may not meet the established standards, requiring additional modifications and corrections, which delay installations and increase costs. The lack of robust PMIs compounds these issues, as common problems persist unchecked, such as misaligned installations, structural damage, and unsafe placements.

Misalignment between the interests of MNOs and third-party firms, which are often incentivized to maximize their output, continues to be a challenge with the hybrid approach. This "half-in" approach frequently leads to significant deviations in standard interpretation or enforcement. MNOs may issue standards but lack the staff, knowledge, and focus to enforce them properly. Third-party firms often choose engineering firms based on price rather than qualifications, driven by their own profit margins/markups, which the MNO does not cap. This can result in decisions favoring more expensive replacements over cost-effective modifications, delays in deliverables, and failure to utilize historical data for future planning. These issues highlight the need for stronger enforcement mechanisms and better alignment of third-party practices with the MNO's goals.

4.4 Model 4: Hybrid Approach – Smaller Carriers

The hybrid approach often adopted by smaller carriers presents unique challenges and opportunities. Smaller carriers typically construct infrastructure as needed, which often limits the development of long-term relationships with vendors. This ad-hoc approach can result in a lack of consistency and quality in engineering services, as the carriers frequently engage vendors who may lack deep industry expertise or an understanding of established standards such as ANSI/TIA-222 and ANSI/TIA-322. This creates inefficiencies as vendors may fail to apply critical practices like 30-degree wind analysis or CFD in their evaluations. Consequently, these carriers often "reinvent the wheel," overlooking more effective and economical solutions due to limited knowledge of available alternatives. A key consideration for smaller carriers is ensuring proper vetting of professionals, selecting teams familiar with industry standards and adept at balancing code compliance with cost-effective solutions.

Smaller carriers often maintain ownership of their infrastructure. However, this ownership is not always accompanied by a strategic focus on long-term maintenance or the monetization of assets through co-location opportunities. As a result, smaller carriers may miss revenue-generation prospects and fail to manage their infrastructure's lifecycle proactively. They also face the ongoing challenge of monitoring and addressing installation faults. Without robust mechanisms like Mapping and Condition Assessments (MC&A) and Post-Modification Inspections (PMIs), recurring issues such as structural inconsistencies and misaligned installations can remain unresolved, driving up costs and creating inefficiencies. [1][2]

While smaller carriers may strive to do the right thing, they must assess and build competent teams that align with their goals and ensure adherence to industry standards and best practices. This approach allows for effective infrastructure management and better communication throughout the structure's total life cycle. It enables carriers to leverage economical, compliant solutions that minimize inefficiencies while ensuring long-term sustainability.

International Perspectives

Globally, variations of these models are observed. Strict data protection laws in Europe encourage centralized management akin to Model 1. Conversely, in parts of Asia, cost-driven approaches align more closely with Models 2 and 3 due to differing market dynamics and regulatory landscapes.

Conclusion

Each business model presents distinct advantages and challenges, influenced by the MNO's priorities and available resources. While model 1 offers the most comprehensive benefits through cost savings and data integrity and is recommended by the MIEC, it requires management commitment by the MNOs. Models 2 and 3 provide operational simplicity but often result in higher long-term costs and inefficiencies. Considering immediate and future implications, an informed decision-making process is essential for optimizing structural engineering outcomes.

5. Consortium Experience and Key Learning on Structural Engineering

The Mobile Infrastructure Engineering Consortium (MIEC) has been united to tackle critical challenges in structural engineering for the industry. By applying advanced engineering principles, standardizing best practices, communicating, and utilizing cutting-edge software tools, the MIEC's goal is to significantly improve efficiencies at scale for mobile telecommunications infrastructure engineering, construction, and deployments. These efforts have delivered transformative benefits for MNOs, tower owners, and contractors. This section highlights key insights, best practices, and measurable outcomes from the consortium's work.

5.1 Establishing Clarity in Stakeholder Roles and Responsibilities

One of the core tenets of the consortium initiatives that has led to its demonstrable success is clearly defining and enforcing the roles and responsibilities of all stakeholders involved in structural engineering projects. Establishing clarity in all stakeholder roles and responsibilities ensures:

- **Improved project efficiency –** reducing delays and errors by eliminating redundancy and ensuring the most qualified personnel perform tasks.

- **Project objectives are met –** due to stakeholders' responsibilities being explicitly outlined and monitored.
- **Cost savings –** from efficient resource allocation and avoidance of unnecessary expenditures due to overlapping roles and miscommunication among team members.
- **Risk mitigation –** from a reduction in the likelihood of structural failures, safety incidents, and compliance issues.

Conversely, failing to establish and uphold stakeholder roles and responsibilities can result in significant challenges. Miscommunication or unclear accountability often causes critical tasks to be overlooked or duplicated, leading to project delays. Redundant efforts and the need to rectify errors add to project budgets, increasing costs. Poor coordination can result in unsafe installations or oversight of key compliance checks, thereby endangering personnel and infrastructure. Additionally, failures arising from role confusion can harm all parties' credibility, causing reputational damage that undermines trust and future collaboration. By establishing a holistic perspective across all projects, there are also significant cost benefits and efficiency gains for all parties.

5.2 The Accountability of the Engineer of Record (EOR)

An Engineer of Record (EOR) is a licensed professional engineer who assumes responsibility for the engineering aspects of a project. The EOR oversees design, ensures compliance with relevant codes and standards, and is accountable for the project's engineering integrity. A key principle upheld by the consortium is the accountability of the EOR to act as a faithful agent, as defined by the National Council of Examiners for Engineering and Surveying (NCEES) [1]. **This means that the EOR must**:

- ***Be loyal and transparent*** – acting in the best interests of their clients and employers and avoiding actions that could compromise their integrity or the integrity of their profession.
- ***Disclose conflicts of interest*** – that could influence their judgment or the quality of their services.
- ***Avoid multiple compensation*** – not accepting compensation from more than one party for services on the same project unless all interested parties are fully aware and agree to avoid an undisclosed conflict of interest.
- ***Advise employers*** – if they believe that their duties could negatively impact the safety or health of the public or their colleagues.

In compliance with NCEES guidelines, the EOR must operate strictly within their area of expertise, upholding the highest professional standards in their actions and deliverables. Public statements made by the EOR must be objective, truthful, and transparent, reflecting their commitment to integrity. Additionally, EORs are expected to act ethically, lawfully, and responsibly, demonstrating dedication to professional principles. Acting as a faithful agent, the EOR would minimize and communicate any potential onerous assumptions that place liability on the MNO. An example is highlighted below:

An engineering firm initially submitted a failing structural analysis and modification design for the monopole, as shown in Figure 13. However, during review by the MNO's trusted engineer, several deficiencies in the report were identified: Assumed incorrect material grades, assumed inaccurate equipment EPAs, assumed microwave dishes unshielded, and, in the worst case, azimuth, Previous mods assumed to be installed but were not. In addition, even though the pole was overstressed, the firm did not verify the capacity of the foundation. This example demonstrates how an engineering firm, not acting as a faithful agent, uses onerous assumptions and returns liability to the MNO/owner.

Figure 13. Image of a monopole

By adhering to these best practices, EORs foster efficiency, collaboration, and cost-effective, code-compliant structural solutions that balance safety and economic considerations. Some of the more specific roles that the MIEC EOR plays are described below:

- **Engineer of Record (EOR) as a Qualified Engineer for General Contractors (GCs)**

  The EOR plays a critical role in supporting general contractors (GCs) by promoting quality, safety, and efficiency in project execution. This includes providing tailored training and resources designed to ensure successful installations. Training topics typically include interpreting construction plans, understanding engineering deliverables, and offering detailed guidance for producing code-compliant Post Modification Inspection (PMI) documentation. Consistent communication, especially in providing detailed PMI guidance, further ensures that GCs clearly understand project expectations.

  It is also critical for the EOR to adopt a holistic approach by evaluating the mount analysis (MA), architectural and engineering (A&E), and structural analysis (SA) packages to verify that GCs have everything they need to execute successful installations and project close-outs. As needed, the EOR provides qualified engineering reviews of construction plans and offers timely support for on-site questions related to design or alternative engineering solutions. This close collaboration between the EOR and GCs fosters smoother workflows and minimizes delays in the field. An example is highlighted below:

  Reference Figures 14 and 15: Issue—An unforeseen in-field issue with a modification design occurred. The GC reached out to the EOR while on-site with the following inquiry: "The main issue is that due to the new support rail being installed above the bottom support angle, we cannot get the v-bracing angles to be completely flush on the face attachment, and if we rotate the attachments down, the angles make contact with the sector frame."

  EOR approved installing the face horizontal in a different location if additional angle crossovers were installed. This alternate solution was provided to the contractor within 30 minutes of their inquiry. As a result, an effective modification solution was installed, and the GC did not have to remobilize to the site.

Figure 14. Images and illustration of issue escalated to EOR by GC

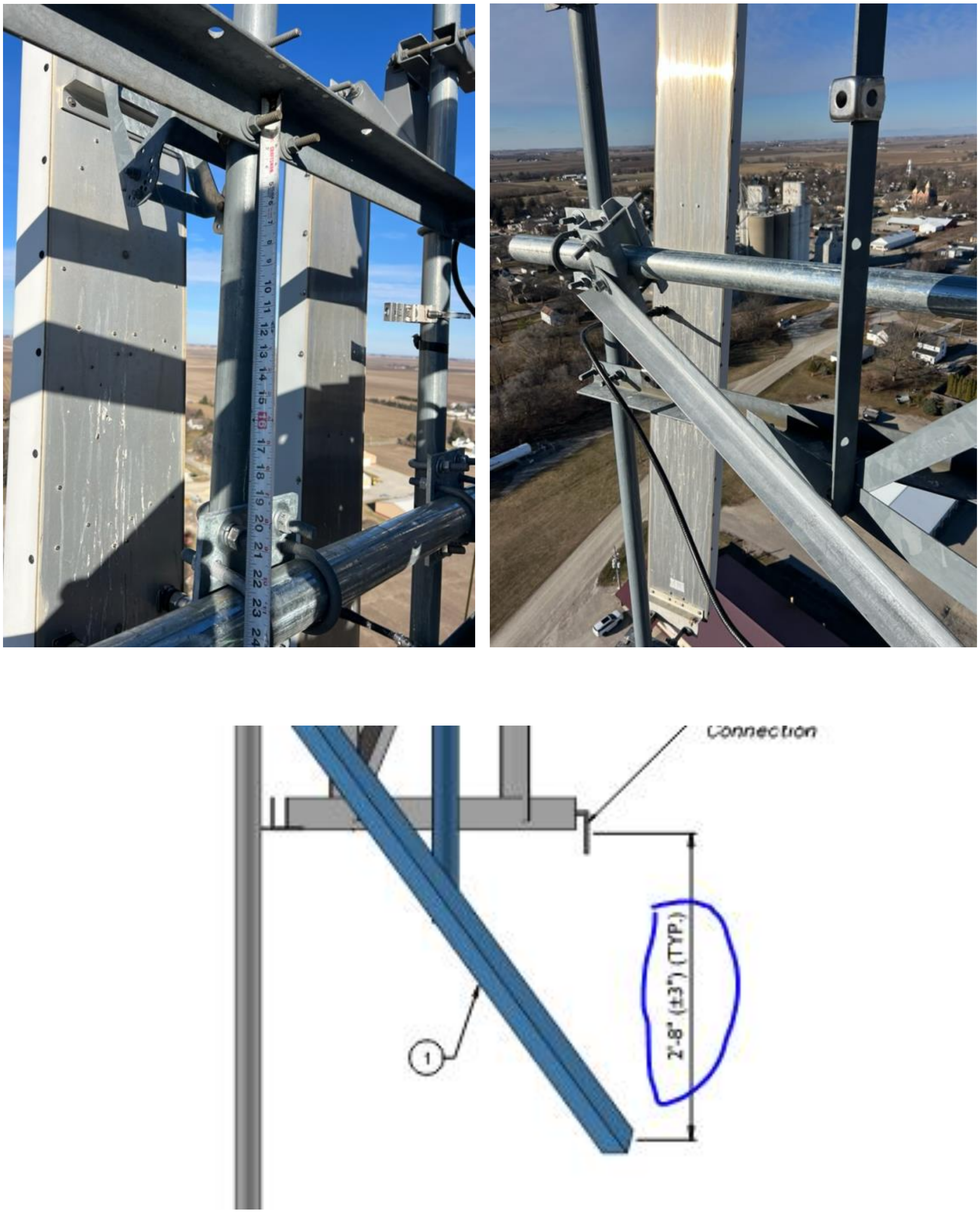
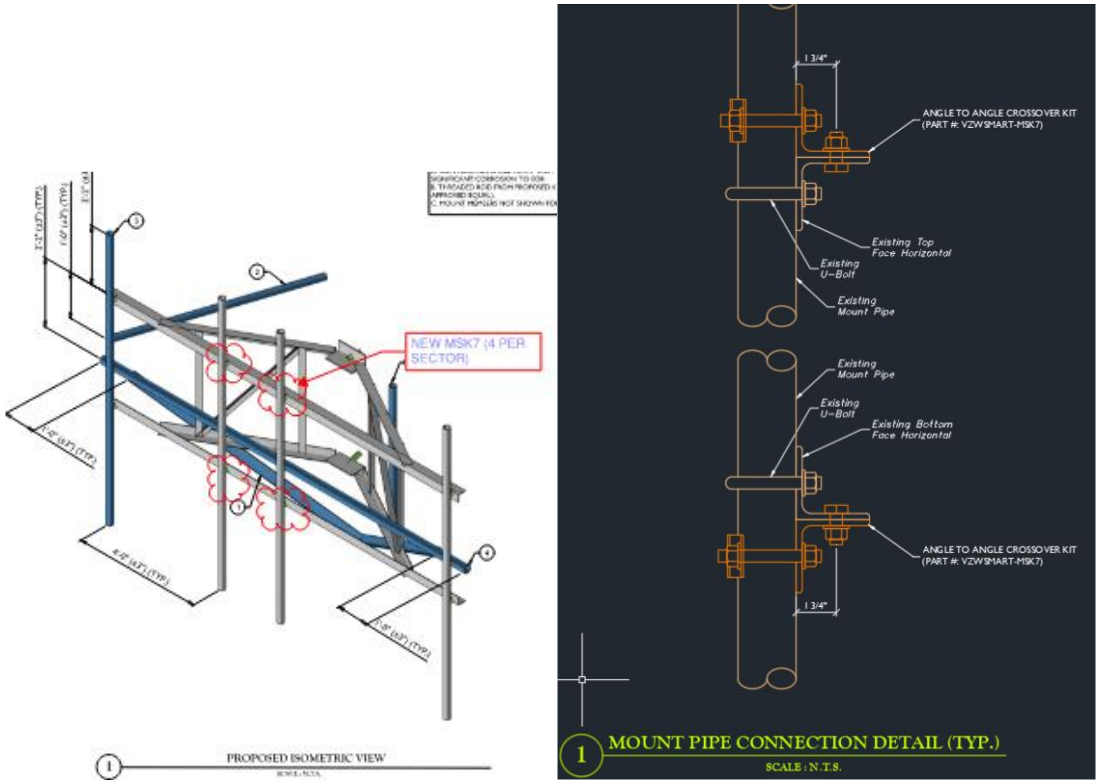


Figure 15. Illustrations of alternate solution provided to GC by EOR



- **Providing Structural Scope and Guidance for Code Compliance**

  EORs are tasked with defining the structural scope of projects and providing guidance on delivering the most economical and code-compliant solutions that align with permitting requirements. In one case study, an MIEC firm was assigned 19 sites where the MNO requested tower mapping and structural analysis services. However, rather than provide a quote for the tower mapping services, the MIEC firm completed the due diligence and utilized its resources to locate the necessary design documents for all these sites. Therefore, no mapping services were required, resulting in 250K USD savings in costs and one (1) month time savings for the MNO.

  The EORs role in defining structural scope is especially critical for complex scenarios such as rooftop sites, where non-engineers may struggle to assess factors like load path, connection integrity, and the impact of proposed loading changes on underlying structures. EORs bring a deep understanding of the required level of rigor for such analyses.

  EORs also evaluate changed conditions and provide detailed cost-benefit analyses to help MNOs make informed financial decisions. For example, rooftop site evaluations may present options ranging from initial destructive mapping to alternative modification designs informed by field conditions.

Figure 16. Image of a telecommunications structure

Figure 16 shows an example of a telecommunications structure on a rooftop where the primary equipment is maintained within a concealment structure. Certain proposed changes to the equipment will likely yield no changed conditions as defined by ANSI/TIA-222 and, therefore, will not require a comprehensive structural analysis; rather, a PE letter would be sufficient.

Regarding mount modifications, cost estimates are included with each failing mount analysis (MA) report, ensuring transparency and actionable insights. The EOR also provides shared carrier letters for water tanks, which streamline the compliance and risk management process.

Figure 17. Images of a round platform with equipment installed at the ~223 ft elevation on the smokestack structure shared by two MNOs.

Figure 17 shows an example round platform with equipment installed at the ~223 ft elevation on the smokestack structure shared by two (2) different MNOs. The non-carrier equipment consists of one (1) GPS unit, two (2) 20’ Omni antennas, & one (1) 10’ tall dipole antenna. This non-MNO equipment causes failures that would require modification, whereas the analysis passes when only the MNO equipment is considered. The EOR proposed relocating the non-carrier equipment to a separate mounting system above the platform.

- **Maintaining Site Documentation and Live Model Data**

  The EOR is responsible for maintaining comprehensive documentation for all sites, ensuring that live model data accurately reflects the equipment installed on-site. This practice supports ongoing operational efficiency and lays the groundwork for future modifications and analyses by keeping records up-to-date and accessible, eliminating the need for future structural mappings. In addition, having live model data on all sites ensures that the MNO will maintain continuous compliance with site lease terms and conditions.

- **Ensuring Engineering Consistency, Constructability, and Code Compliance**

  Engineering consistency is a cornerstone of the Mobile Infrastructure Engineering Consortium’s work. EORs foster consistency and best practices across the industry by conducting internal peer reviews and delivering customer-specific solutions. This approach ensures that MNOs benefit from diverse expertise without over-relying on a single engineering firm and from having the proper application of engineering to their specific use case. Furthermore, EORs are equipped to pivot quickly in response to changes requested by MNOs, ensuring flexibility and alignment with project goals.

Inconsistencies in code interpretation or using outdated standards can lead to significant discrepancies in engineering recommendations. EORs support the MNOs in addressing this challenge by adhering to rigorous audit processes, which highlight and resolve discrepancies. An example is highlighted below.

Figure 18. Image of a pole with reported overstress.

Figure 18 shows an example where an engineering firm submitted a structural analysis with a reported pole overstress of 133%. During the review by MNO's trusted engineering firm, it was identified that the analysis did not adhere to CBC, IBC, ANSI/TIA-222-H, or ASCE 7-16. There were also various errors in modeling, including using 3.5 times the area and 11 times the weight of palm fronds compared to what was installed. When corrected, there was a passing structural analysis result with no required costly modifications.

The MNOs have set constructability of design as an expectation for the EORs, facilitating this through the communication pathway established between EORs and GCs during the PMI process. The MNO also leverages the EOR firms' understanding of constructability during their audit process. Below is an egregious example of a non-constructible design identified during this audit process.

Figure 19. Illustration of pole reinforcement design.

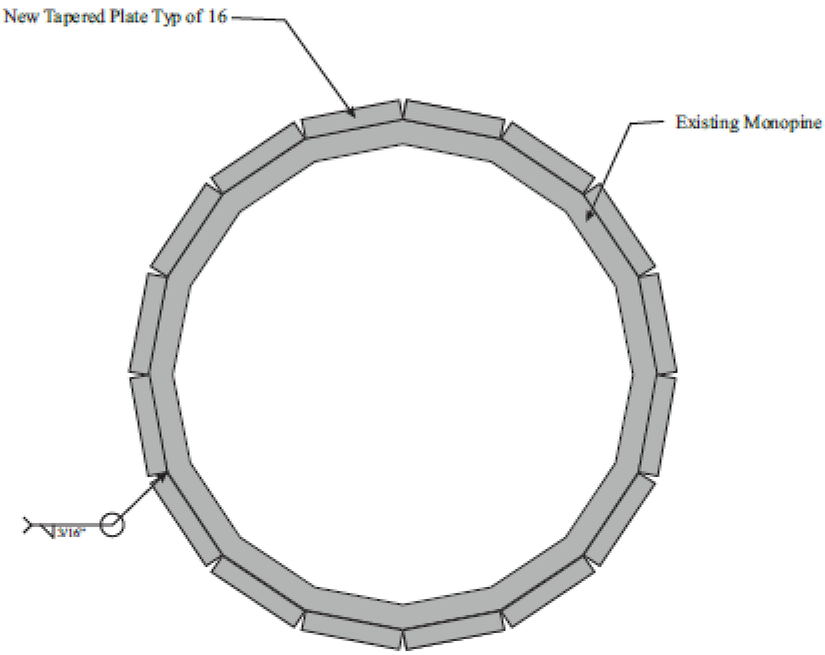


Figure 19 - This pole reinforcement design required (16) tapered flat plates (wider at the bottom than the top) with fabrication tolerances to the 1000th of an inch. This is equivalent to the thickness of a piece of hair. Connection to the tower base plate was not specified or designed, therefore it is not transferring the forces from the modification into the base plate, anchor rods, and foundation. The design called for 621 linear feet of welding with no guidance from the contractor regarding fire protection, welding procedures, and AWS D1.1/AISC/IBC, and the welding was unachievable.

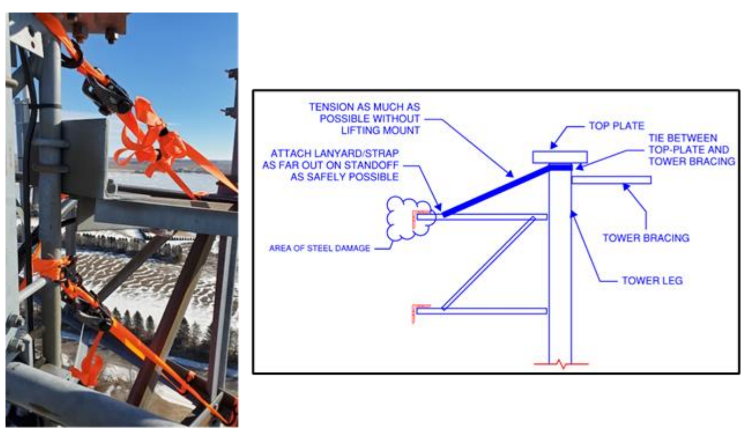
- **Ensuring Safety and Network Performance**

  Safety and network performance are integral to the EOR's responsibilities. Temporary safety solutions, often informed by field mappers and GCs, are implemented under the EOR's guidance until permanent solutions can be established. An example is highlighted below. Considerations for climbing facilities and code-compliant load reduction letters help manage risks while maintaining structural integrity.

Figure 20. Images of cracked standoff member and plastic deformation.

Figure 20 above shows a situation encountered by in-field crews while performing a structural mapping of the mount. It was noted that the standoff member was cracked, and plastic deformation was visually occurring. Per the established process, this was immediately brought to the attention of the EOR, who worked with the crew to approve their installation of a temporary support solution with lanyards and secure the mount from further damage before leaving the site. See Figure 21 below.

Figure 21. Image and illustration of temporary support solution with lanyards.



- **Educating Responsible Authorities**

  EORs play a pivotal role in educating Authorities Having Jurisdiction (AHJs) to ensure informed decision-making. While aiming to comply with reasonable AHJ requirements, EORs are prepared and equipped to discuss with them directly when not reasonable and above and beyond what the code requires. Examples include promoting the concept of intended use [2] so that the appropriate standards for water tanks (e.g., ASCE vs. AWWA) are utilized, demonstrating the reliability of telecommunications infrastructure in terms of both safety and network performance. This collaborative approach fosters trust and compliance amongst stakeholders. An example is highlighted below.

Figure 22. Images of water tank.

Figure 22 shows an example where an engineering firm completed a structural analysis of the above water tank based on telecommunications equipment upgrades utilizing the ASCE standard and a structural overstress was reported. During the review by the MNO's trusted engineering representative, it was determined that the AWWA standard should have been utilized for the analysis based on the intended use of the water tank. Further discussions with the AHJ confirmed proper standard application, and the structural analysis was passed when running with the appropriate standard.

5.3 Project Process Optimization

Optimizing project workflows is a key focus area for the Mobile Infrastructure Engineering Consortium. EORs actively manage tasks across the project lifecycle, including Mapping, Structural Analysis, Structural Modification, PII/PMI, and Re-Analysis, ensuring continuous progress and removing roadblocks.

The PMI (Post-Modification Inspection) and PII (Post-Installation Inspection) processes are pivotal in confirming that all installations and modifications are completed accurately and in compliance with relevant codes and standards. There are several misconceptions about PMI & PII that we aim to clarify below:

I. **PMI & PII are required per code** (reference ANSI/TIA-222 Section 15)

II. **It is recommended that a PMI be conducted when structural modifications are involved**, as well as when simple equipment changes are involved, as changes in equipment location will impact the structural analysis results.
III. **A PII needs to be completed for a new mount installation** – several aspects of a new mount installation may be done incorrectly, altering the structural analysis results. It is also important to verify that the GC selected the correct mount as specified by the EOR.
IV. **To ensure the best outcome, a PMI or PII should be completed by the EOR working directly with the general contractor and not independently by a third-party firm.** The MIEC has successfully completed PMIs on more than 30,000 sites through a desktop PMI based on information provided directly from the GC during installation.
V. A PMI or PII can only be effectively conducted by the design's EOR. Often, other MNO representatives are focused on various aspects of the equipment installation and are not focused on or have the proper expertise to verify engineering design specifications.

These inspections validate that structural modifications meet engineering specifications, ensuring the work adheres to initial designs and satisfies all safety and performance criteria. By verifying compliance at these critical junctures, the PMI and PII processes mitigate risks of structural failure, reduce liability for MNOs, and support the long-term reliability of telecommunications infrastructure.

Moreover, the thoroughness of these inspections helps close verifiable engineering assumptions made during the design phase, allowing for greater confidence in the site's structural integrity. This process ensures a live and accurate model is maintained for future re-analysis, reducing redundant efforts and optimizing resource allocation. The proactive management of PMI and PII activities also significantly reduces the need for GC remobilization, creating cost efficiencies and promoting a seamless workflow.

The consortium introduced the concept of re-analysis on subsequent projects when a PMI was completed on the initial install, to help drive long-term efficiencies by eliminating the need for repetitive site mappings. This approach streamlines future modifications and inspections, ensuring that project timelines remain on track and resources are used effectively. By confirming code-compliant installations and facilitating continuous progress, these optimized workflows enhance the overall reliability and safety of the telecommunications network.

5.4 Economical, Efficient & Innovative Solutions

The consortium emphasizes economic and efficient solutions, which are vital for overcoming the logistical and financial challenges inherent to telecommunications infrastructure projects. When traditional site access is limited or costly, EORs employ innovative techniques such as desktop mount mapping, which leverages geometry verification from installing contractors to provide up to 80% of structural data without needing full on-site mapping. This approach reduces costs and expedites project timelines by minimizing assumptions and focusing on critical member sizes and mount pipe layouts.

Another key practice involves delineating serviceability issues from structural failures, particularly on T-Arms. This nuanced analysis has significantly reduced failing reports by addressing issues that do not require structural modifications. Additionally, the implementation of clear delineation and communication with installing contractors regarding hardware upgrades has further reduced the frequency of modification drawings, enhancing overall project efficiency.

By applying stringent engineering designs and processes, the Mobile Infrastructure Engineering Consortium has avoided unnecessary and costly mount replacements at scale. This generates substantial cost savings, minimizes the need to take sites off the air during modifications, and follows MNO guidance on handling items regarding potential network reliability [3]. For MNOs, the reduced downtime translates directly into preserved revenue streams and improved network availability, demonstrating the critical intersection of engineering precision and operational efficiency.

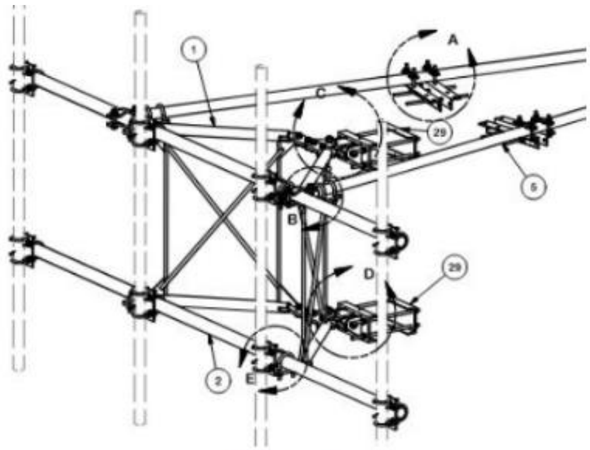
5.4.1 Mount Modification Standardization

Mounts

Mount modifications represent a collaborative and innovative aspect of the Mobile Infrastructure Engineering Consortium's work. By focusing on modifications rather than complete replacements, the consortium can ensure that the MNO can maintain uninterrupted service. Using stringent engineering designs ensures that modifications are economical and structurally sound, avoiding the unnecessary costs associated with full replacements.

A standout achievement in this area that drives cost reduction is the development of over 20 standardized bolt-on steel modification kits created in collaboration with industry manufacturers and suppliers. These kits address more than 85% of retrofit scenarios without requiring custom designs, allowing contractors to select parts based on inventory, price, or preference. Standardization has reduced the lead times of steel to less than three weeks nationally, streamlining project schedules. An example is highlighted below:

Figure 23. Illustrations of same mount kit (v-frame) produced by two different manufacturers.



VFA12-HD

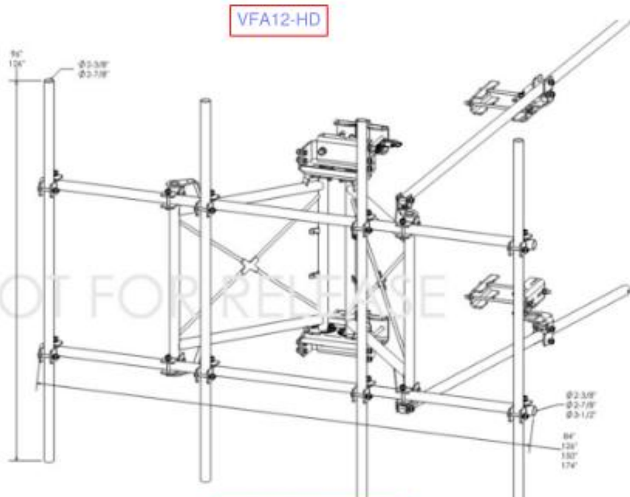


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Figure 23 shows the same mount kit (v-frame) produced by two different manufacturers. This eliminated the long-standing issue of EORs specifying a new modification kit “or equivalent” and the GC determining what “or equivalent” is without consulting with the EOR. This can lead to a potentially ineffective solution that has to be remedied via an additional structural modification on the subsequent project (example below). With standardized kits, the GC no longer has to worry about finding an alternative option since the same kit is stocked by multiple distributors and offered by multiple manufacturers nationally.

Figure 24. Illustrations of proposed and installed mounts.

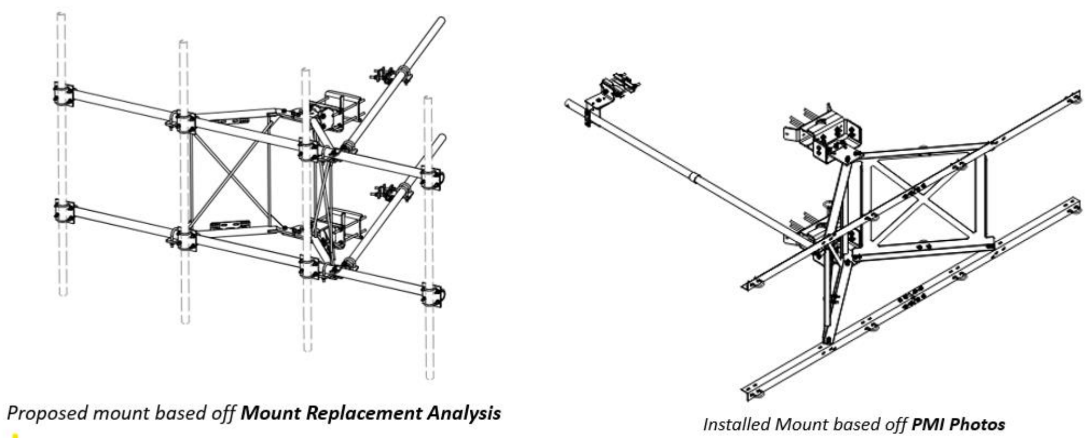


Figure 24 shows a new mount specified by the EOR and the one the contractor selected. Not only is the new mount structurally inefficient for the mount loading and will require further structural modifications, but the new mount has flat vs. round members, which has an increased projected area and will adversely impact on the underlying tower capacity. Furthermore, if the MNO does not do a PMI to allow this issue to be corrected, they are at risk for lack of code compliance. Not only did they pay the contractor in full to perform an ineffective installation, but the MNO will not be paying for a required future upgrade out of their own pocket.

Through these efforts, manufacturers gained a deeper understanding of MNO and tower owner's needs and were able to educate GCs on effective implementation. Feedback from GCs informed the design of these solutions, ensuring alignment with field challenges and enhancing workflows. The consortium also facilitated collaboration among manufacturers, MNOs, tower owners, and GCs to create solutions that drive quality, safety, and efficiency across projects. By prioritizing modifications over replacements, the consortium delivers tangible benefits regarding cost savings, reduced downtime, and enhanced project outcomes.

Towers

The consortium has developed innovative solutions that address some of the key challenges faced by MNOs and Tower Cos. By considering that aerial welding is one of the key challenges from both a cost and safety perspective, a modification solution was developed that delivered steel reinforcement to strengthen a monopole that not only eliminated the need for any field welding but also significantly reduced the number of bolts required for pole attachment. This solution incurs 20%-30% less cost than traditional solutions.

Corrosivity of soil is a particular challenge for guy anchor foundations, as it leads to steel loss in the anchor member connecting the guy wire to the foundation, which is a critical member. While traditional industry methods require the addition of new guy anchors to remediate this issue, the consortium provides a solution that allows the existing guy anchor foundation to be remediated, leading to significant cost and time savings.

Figure 25. Image of Congruex's patented Guy-Lock^{TM} solution [4]

A common failure point for concealment poles is the slender steel spine the antennas attach to inside the canister. Traditional industry solutions may require a full drop and swap pole replacement. The consortium has developed a structural modification solution that allows for local modification of the steel spine without taking the MNO equipment off-air and with no service disruption. The typical savings for this solution is up to 50% over traditional methods.

Figure 26. Image Congruex's patented Spine Saver™ solution [5]

5.6 Summary

High-quality deliverables are crucial for efficient, cost-effective, and code-compliant installations. The Mobile Infrastructure Engineering Consortium has set a new benchmark for excellence in mount structural engineering by fostering collaboration, promoting consistency, and leveraging innovative solutions. These efforts enhance the reliability and safety of telecommunications infrastructure, delivering tangible value to MNOs, tower owners, and contractors alike.

When MNOs utilize engineers that focus on designs that yield quality installations, costs are reduced because contractors are required to communicate effectively. Quality engineering minimizes rework and enhances network reliability and redundancy. MNOs save money by avoiding the replacement of failed mounts or damaged radios due to issues like water ingress or stray currents. This approach also provides an opportunity to avoid unplanned costs and reduce installation faults.

6. Revolutionizing Wireless Site Structural Analysis Through Advanced Technologies

Wireless site structural analysis is a well-established domain of the telecommunications industry with robust engineering methodologies. While mathematical calculations needed to validate structural integrity for required site modifications are well understood, technological advancements such as digital twin, artificial intelligence (AI), machine learning (ML), and augmented reality (AR) offer new opportunities to streamline analytical processes and improve workforce efficiency. This section explores the potential impact of these technologies, beginning with the importance of obtaining accurate, comprehensive, and up-to-date wireless infrastructure site data to facilitate effective structural analysis.

6.1 Methodologies for Wireless Site Structural Data Collection

Accurate and timely collection of wireless infrastructure data is essential for network planning, improving efficiency, predicting failures, reducing costs, and deploying innovative technologies. Maintaining a historical record and continuously updating this data is critical for maximizing the benefits of advanced technologies such as AI and ML, which are only as effective as the data they are trained on.

In the context of structural analysis, maintaining precise data on towers, poles, and mounts is indispensable. Structural analysis relies heavily on accurate and up-to-date measurements of these components. Beyond accuracy, data completeness and currency are key drivers of operational efficiency and cost reduction in structural analysis projects. Regulatory requirements for periodic site maintenance, increasing network capacity demands driven by wireless traffic growth, deployment of new technologies aligned with 3GPP standards, and weather-related events necessitate ongoing upgrades and maintenance of wireless infrastructure. Constantly collecting and maintaining accurate infrastructure data has become a vital industry activity. Some of the various methods for collecting wireless infrastructure data are summarized below:

- **Drone Data Collection:** Drones have become an increasingly popular tool for data collection in wireless infrastructure projects. With advanced sensors, cameras, and mapping technology, drones enable real-time, high-resolution data capture to create detailed virtual models [6] [7]. Drone imaging is particularly useful for identifying the type, size, and general location of mounted radios and evaluating site environments. Below are some examples of drone-captured images.

Figure 27. Images of Mount Captured from Drone

However, drones often fall short in providing precise measurements needed for code-compliant structural analysis due to challenges in accessing critical failure points, mechanical components, and the intricacies of mounts and other equipment.

A detailed case study published by NATE [2] demonstrates the limitations of drone-collected data, finding that only 7 out of 12 defined tolerances could consistently be derived from drone operations. Even at sites where drone-collected data may be helpful, in many cases, the site's unique situation often necessitates additional drone flights and supplementary manual collection to meet structural analysis needs. After the initial cost of a drone flight, there are many cases with follow-up costs associated with additional drone flights and significant engineering rigor to ensure correct information is captured for analysis. This is cautionary information for MNOs who are led to believe that drones are the 100% solution for all site data capture. They are a great tool and helpful but, in most cases, not entirely reliable for ensuring high efficacy with engineering analysis.

Figure 28. Image and illustration of mount-to-tower connection.

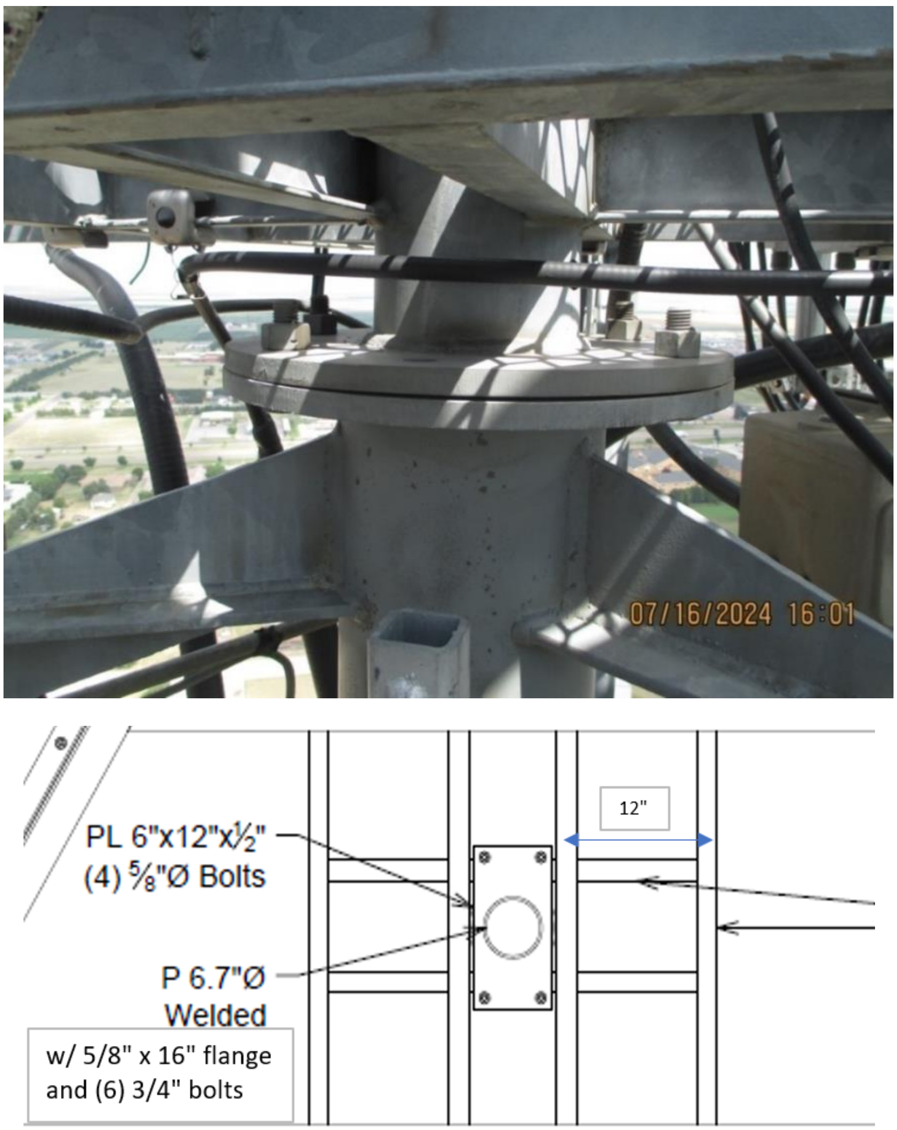
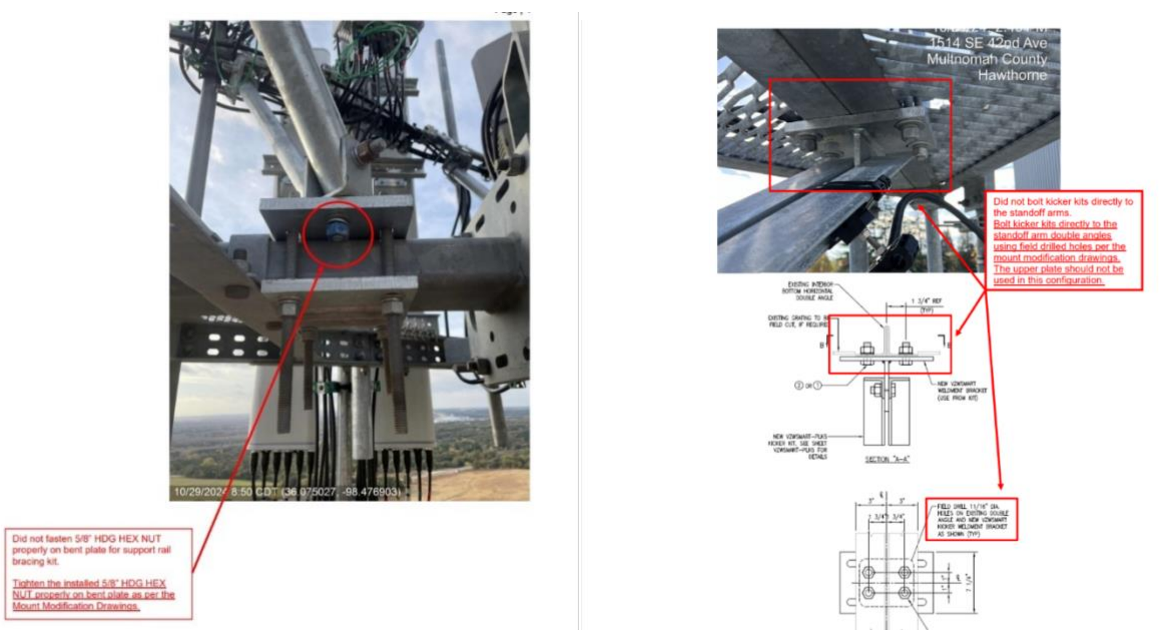


Figure 28 shows a relatively complex mount-to-tower connection where necessary information would not be feasibly gathered via drone; rather, physical mapping would be needed.

- **Manual Data Collection:** Manual data collection, performed during maintenance and inspection activities such as PMI and PII, provides highly accurate and reliable data essential for structural analysis. Unlike drone data, PMI and PII results include precise measurements, detailed condition assessments, and close-range images that confirm structural integrity. While more labor-intensive, manual methods ensure superior data quality and compliance with regulatory standards. These inspections also undergo architectural and engineering (A&E) review processes to validate the data's accuracy and completeness. Drone PMI data alone will leave the MNO with incomplete information, leading them to potential liability and future need for structural mapping services in their subsequent projects.

Figure 29 shows real-world examples of PMI, maintenance, and condition-based human-collected data that are indispensable for ensuring the quality of structural analysis and nearly impossible to gather through other means, including drones.

Figure 29. Images and illustrations of maintenance and conditioning report data.



- **Wireless site documentation:** Wireless site documentation, including manufacturing specifications for towers, poles, mounts, and equipment, is a valuable complimentary data source for structural analysis. Automating the extraction of this text-based information from its original sources can streamline the data integration into structural analysis workflows.

- **IoT-embedded devices:** Emerging technologies, such as IoT-embedded devices, also show promise for continuous structural data collection. While this method of collecting wireless infrastructure data has only been utilized to date in a small number of instances, examples from its use across other industries suggest significant potential for real-time monitoring and analysis.

As described above, wireless infrastructure data is collected and stored through various means, often leading to challenges in the industry. Data is typically housed on different platforms, in disparate formats, and captured at different times, resulting in inconsistencies and an unreliable source of truth. These challenges are particularly pronounced in multi-MNO tower collocation scenarios, where multiple MNOs own and manage mounts on the same tower. In such cases, an MNO may be unaware of changes made to structural components by other MNOs, potentially affecting their own planned network upgrades. Addressing these issues requires the wireless infrastructure industry to adopt standardized processes and methodologies for collecting, updating, and managing asset data.

Another critical consideration is secure and managed access to wireless infrastructure data, which is essential for national security. Organizations must implement limited and controlled access protocols based on roles and responsibilities, including subcontracting entities. A cloud-native, multi-tiered, role-specific architectural approach could be a robust solution for ensuring secure and efficient management of this data.

6.2 Developing cost-efficient digital twins with accurate structural engineering data

A digital twin is a virtual representation or simulation of a physical object, system, process, or environment that mirrors its real-world counterpart in real-time. By integrating data from sensors, historical sources, and other inputs, digital twins enable network providers to simulate behaviors, predict performance, and optimize operations, playing a pivotal role in their organization's digital transformation.

Digital-twin technology has grown exponentially, especially in highly operationalized industrial environments. Market research indicates that the digital-twin market is projected to grow at a compound annual growth rate (CAGR) of 50% between 2020 and 2030, reaching an estimated value of $184.5 billion USD. Investments in well-implemented digital twins reportedly yield a 6:1 return on investment [3]. While the use of digital twins is still evolving across the wireless industry, their application has demonstrated significant value in industries such as agriculture for crop and livestock monitoring, healthcare for virtual patient care, and manufacturing for process optimization [3].

Two critical aspects define the digital-twin concept:

1. **Accurate Data Collection and Storage**: Functional and reliable digital twins depend on precise and comprehensive data-capturing methodologies that accurately reflect real-world conditions.
2. **3D/Virtual Representation of Data**: This visualization enhances understanding, analysis, and productivity.

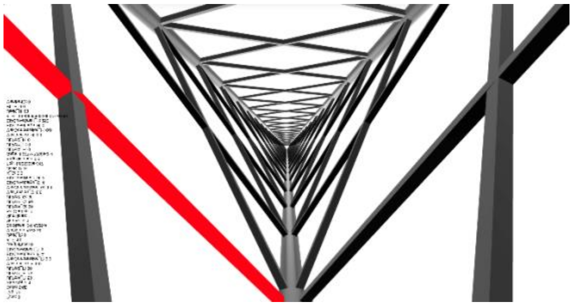
The fidelity of data collection is paramount for wireless infrastructure engineering, particularly for tower and mount structural analysis. High-precision data is necessary to ensure the validity of structural analyses, such as knowing the exact thickness of a metal tube or the precise dimensions of a tower structure. Manual collection methods may be indispensable when such data is unavailable to achieve the required accuracy and reliability.

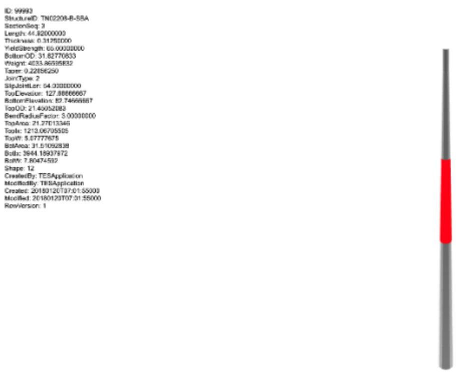
The 3D visualization provided by digital-twin technologies further improves workforce productivity and safety. For crews working on wireless sites, having a highly accurate digital-twin representation of towers, mounts, and other structural components allows for better preparation and planning. This reduces risks for personnel operating in challenging environments, such as significant heights, complex mechanical structures, or adverse weather conditions. Additionally, digital twins expedite decision-making processes, such as evaluating multi-tenant co-location requests, by offering immediate access to visually intuitive and detailed structural representations.

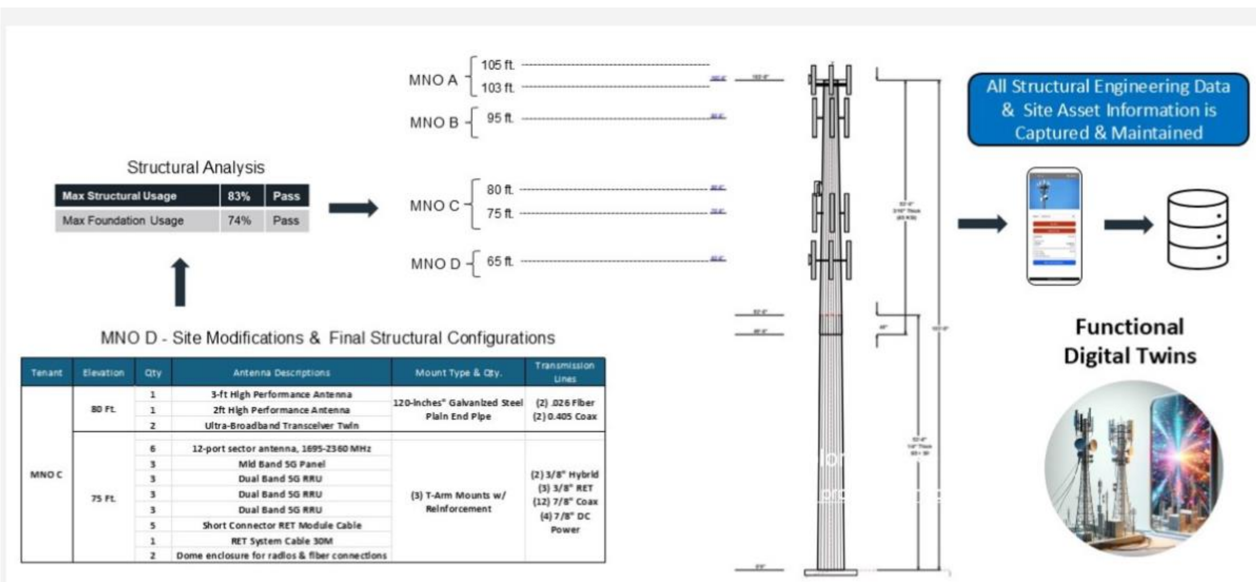
Figure 30 illustrates the digital twin of a monopole created using highly accurate structural data collected manually. The data is visualized within the structure, focusing on the area of interest.

While the topic of 3D visualization and rendering technologies extends beyond the scope of this paper, it is important to note the significant advancements made over the past few decades. Innovations in areas such as virtual reality (VR), augmented reality (AR), game design, and computer-aided design (CAD) have greatly enhanced 3D modeling tools and technologies. References [8], [9], and [10] provide an overview of 3D file formats, modeling software, and ongoing efforts to unify approaches within this domain.

Figure 30. Illustration of digital-twin wireless structures generated based on precise data.







Functional digital twins using structural engineering and site asset data

6.3 Applicability and Benefits of AI Technologies

Recent advancements in artificial intelligence (AI) and machine learning (ML) offer transformative opportunities to enhance wireless site structural analysis and asset management. Key applications include:

- Predictive Structural Failure Analysis
- AI-aided Planning for Network Deployment and Expansion
- Enhancing Structural Analysis Efficiency with RAG-AI models and LLM-Powered Information Extraction
- Wireless Remote Site On-Device AI
- Augmented Reality (AR) for Enhanced Engineering and Construction

This section highlights these areas and explores how AI/ML technologies can be applied effectively.

6.4 Structural Failure Predictive Analysis

Wireless sites are frequently exposed to weather events and various environmental stressors that may degrade physical assets at these sites and affect their overall structural integrity. The towers, mounts, and other network infrastructure installed at the sites are all subject to environmental risk and regulatory mandates imposed to ensure safety standards must be continuously upheld. MNOs and tower owners require regular maintenance and inspections for continuous regulatory compliance and to ensure these wireless networks maintain high service availability for mobile users.

Combining historical and real-time asset management data with drone imagery significantly enhances structural failure analysis and detection. While drone images alone lack the precision required for reliable analysis, as noted in section 7.1, combining them with AI models trained on historical data - including human-captured images of structural failures - transforms structural analysis into a robust predictive tool.

Supervised learning models, continuously updated with new, comprehensive datasets, can process inputs to predict structural vulnerabilities accurately. To maximize their effectiveness, the training process should be a dynamic, ongoing workflow that evolves as new data becomes available. This involves pre-characterizing and structuring the training data and drone footage around critical wireless infrastructure elements (towers, mounts, radios, etc.) and having detailed features and descriptions of their mechanical components.

This approach enables highly accurate predictive classification by leveraging AI/ML models that integrate visual, textual, and numerical data. Structuring the data in this manner ensures that the models achieve both precision and adaptability in their analyses and predictions.

Figure 31 demonstrates how human-captured images provide foundational training data for AI-enhanced structural analysis.

Figure 31. Image of drone inspecting a tower and a structural fault

Today, MIEC member organizations possess millions of similar structural images that could be used to train AI models via supervised learning.

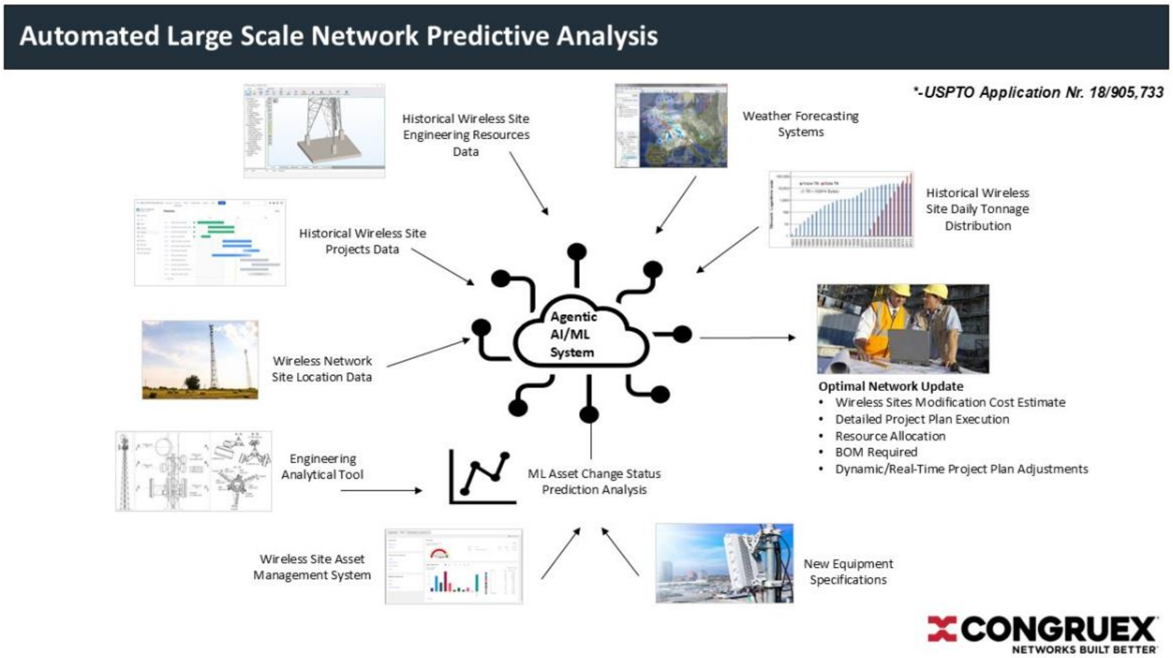
6.5 AI-aided Planning for Network Deployment and Expansion

MNOs frequently upgrade their wireless networks to accommodate new technologies such as 4G-LTE, 5G, and 5G-A, add capacity and integrate additional spectrum, or take advantage of advancements in RF performance, such as Massive MIMO systems with various configurations. These upgrades require meticulous and complex planning, encompassing considerations like resources, site locations, timelines, and equipment availability.

AI and machine learning technologies can streamline these upgrade processes by conducting advanced analyses to deliver automated, predictive project planning and cost allocation. These tools can also adapt to real-time changes, accounting for project progress, unforeseen events, weather conditions, and equipment availability.

Figure 32 below illustrates a large-scale predictive analysis solution for network planning proposed by a TIF and MIEC member, demonstrating significant potential value for MNOs.

Figure 32. Illustration of large-scale network predictive analysis solution.



This proposed solution relies on a comprehensive dataset, including historical information on wireless structure conditions (e.g. towers and mounts), site geographical locations, project durations and costs, availability and ratings of engineering and construction resources, real-time weather data, and average daily traffic distribution at wireless sites. By utilizing this extensive data, the AI/ML predictive analysis can develop a project plan optimized for cost, resource allocation, execution, and timing while ensuring minimal disruption to network services. Additional details about this implementation are available in [11].

6.6 Enhancing Structural Analysis Efficiency with RAG-AI Models and LLM-Powered Information Extraction

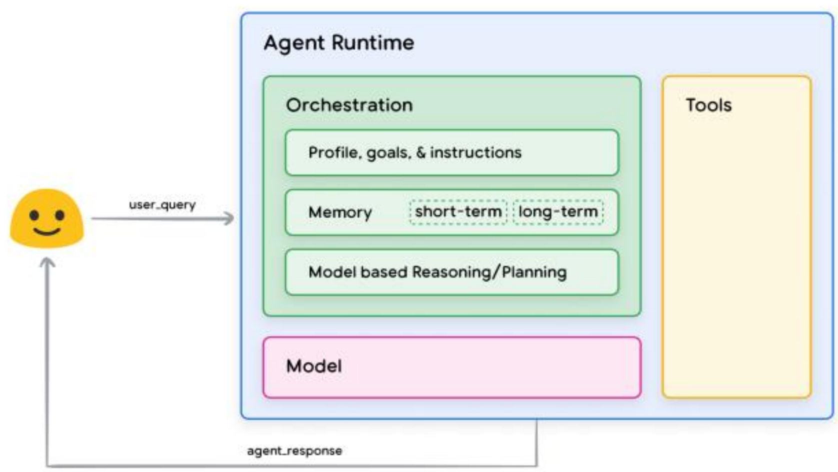
Structural analysis of towers and mounts relies on finite element software tools like RISA, which require numerous input parameters, such as mechanical component specifications, radio/antenna dimensions and weights, and compliance with local, regional, and/or federal regulatory standards. However, structural engineers often face challenges when these parameters are not readily available, requiring time-consuming, inefficient manual searches across public and private domains. Leveraging Retrieval Augmented Generation (RAG) and large language models (LLMs) can streamline this process by automating information retrieval and eliminating inefficiencies. This innovation transforms a tedious manual step into an efficient, automated process, saving valuable time in structural engineering analysis.

Additionally, generative AI (GenAI) and RAG models offer significant potential for various applications in structural engineering. These applications include:

- Generating loading placement diagrams for construction drawings (CDs).
- Automating the creation of structural analysis reports.
- Accurately applying equipment loads in finite element analysis (FEA) models.
- Improving software tool integration with different data storage systems.
- Enabling knowledge extraction and validating sensitivity analysis through text-based prompts.

The emergence of Agentic AI systems is also another area of interest when it comes to wireless infrastructure structural engineering projects. Agentic AI systems refer to autonomous multi-step task executing systems that combine reasoning with access to external data to achieve a goal. Agentic systems extend the power of language models by integrating them with methods for reflection, tool use, planning, and collaboration, all very applicable to the domains of interests addressed in this paper. The figure below depicts the architecture of an Agentic-AI implementation framework [16].

Figure 33. Illustration of general agent architecture and components.



6.7 Portable AI-Powered Solutions for Real-Time On-Site Decision Making

The benefits of AI technologies extend beyond back-office wireless infrastructure analysis. Engineering structural analysis typically produces reports and diagrams used by construction crews to implement instructions for reinforcing towers and mounts, replacing mounts, or installing new radios. However, these instructions are often complex and may require real-time communication between crews and structural engineers to ensure proper implementation and compliance with regulatory standards.

A significant challenge arises when construction crews lack reliable wireless connectivity with back-office engineers. This can occur when a site is deactivated or nearby sites fail to provide sufficient coverage, such as in remote or rural locations. In such cases, crews may need to return to their base and revisit the site after consulting with engineers, resulting in delays and increased costs.

AI-powered solutions on mobile devices, such as smartphones, tablets and laptops, offer a way to address these challenges. AI can streamline operations by enabling construction crews to access local intelligence directly without requiring back-office connectivity. AI models can be trained in data centers while the inference step runs locally on-device. Additionally, small to medium-sized AI models have proven to run efficiently on smartphones. The capability of smartphones to support AI models depends on hardware factors like CPU, GPU, RAM, and model optimization. Recent advancements, such as the Qualcomm Snapdragon 8 Gen 3 mobile platform, support generative AI models with up to 10 billion parameters running on-device [12].

Figure 34 below shows an on-site direct device connectivity architecture allowing efficient and optimized remote multi-modal AI workload execution that significantly enhances crew operation and data collection.

Figure 34. Illustration of on-site direct device connectivity architecture.

Furthermore, this solution allows efficient off-loading of wireless site data collection based on a dynamic time-location based on a 5G-Advanced network slicing feature. A detailed description and benefits of this solution is provided in [13].

6.8 Enhancing Structural Engineering Through Augmented Reality

Augmented Reality (AR) enriches real-world objects by overlaying computer-generated perceptual information across multiple modalities, including visual, auditory, haptic, and somatosensory [14]. AR aims to provide an enhanced version of the physical world. Although AR is not a new technology, recent advancements in hardware, computer vision software, and human sensory devices have significantly increased its practical feasibility and relevance. AR has found applications across industries such as education, healthcare, automotive, entertainment, manufacturing, and construction [14,15].

Figure 35. Image of a typical example of AR application in industrial environments.

More recently, AR has garnered attention in the wireless infrastructure industry, where its potential to improve understanding and productivity in construction work is being explored. In structural engineering and wireless site construction, AR presents two key areas of potential benefit:

1. **Enhanced Structural Engineering Designs**:
   AR can transform traditional 2D CAD designs into interactive, immersive environments for structural engineers. This provides a more comprehensive understanding of mechanical structure locations, step-by-step installation procedures, and the angular positioning of radios and antennas. Such

enhancements enable better planning and visualization of engineering designs and help engineers assess constructability.

2. **Improved Construction Workforce Productivity**:
   AR can offer interactive experiences to guide construction crews through tasks such as installing and reinforcing mount structures and other components. By accessing AR-augmented CAD designs on mobile devices—such as smartphones, laptops, or AR glasses—construction crews can execute tasks more efficiently and with minimal reliance on back-office engineers. This autonomy is especially valuable for crews in remote locations with limited or no internet connectivity.

Figure 36. Image of onsite data capture using mobile device.

Recent advancements in mobile hardware and AR platforms have made these applications feasible. Tools like Apple's ARKit and Google's ARCore support motion tracking, surface detection, and lighting estimation for integrating AR elements into the real world. For example, iPhone models with LiDAR scanners, such as the iPhone 14 Pro, enable accurate depth sensing, real-time holographic overlays, and enhanced object placement for AR applications.

Combining AR with AI technologies amplifies its potential, offering real-time translations, contextual information, and personalized content. This synergy creates a more intuitive and efficient engineering experience [14].

Adopting these advanced technologies should follow a phased approach, starting with applications that provide the most operational, time-saving, and cost-effective benefits. Early stages may require human intervention to train and fine-tune AI models, emphasizing reinforcement learning supported by reliable data. This incremental path ensures a smoother transition and maximizes the impact of AR in structural engineering and wireless site construction.

7. Conclusions

The telecommunications industry is undergoing rapid transformation, with the expansion of 5G and the early stages of 6G deployment driving unprecedented demand for structurally sound, scalable, and cost-efficient network infrastructure. The ability to deploy and maintain this infrastructure effectively depends on establishing structural engineering best practices, maintaining accurate data management, and adopting advanced technologies.

Structural Analysis: A Cornerstone of Network Reliability

The structural integrity of telecommunications infrastructure is critical for ensuring safety, regulatory compliance, and long-term cost efficiency. Every new deployment, modification, or upgrade requires a comprehensive engineering assessment to prevent failures, costly rework, and delays. The white paper has highlighted how standardized structural analysis methodologies, and the application of engineering best practices can significantly reduce costs and accelerate network expansion.

Data Management: Enabling Efficient, Scalable Growth

Accurate, well-maintained data is essential for optimizing structural analysis, reducing redundant engineering efforts, and enabling predictive maintenance. A lack of reliable site data results in delays, unnecessary costs, and engineering inefficiencies. Leveraging digital twins, AI-driven data analytics, and centralized data repositories can help network operators maximize asset utilization and long-term operational efficiency.

Leveraging Advanced Technologies for a More Efficient Future

Emerging technologies such as Artificial Intelligence (AI), Machine Learning (ML), Augmented Reality (AR), and digital twins offer unprecedented opportunities to improve efficiency, accuracy, and cost-effectiveness in telecommunications infrastructure management. These innovations can enhance predictive analysis, automate structural assessments, and optimize network planning, enabling faster deployments and long-term operational savings.

TIF's Role in Industry Advancement

The Telecommunications Industry Foundation (TIF) has established industry-wide best practices, educated stakeholders on codes, regulations, and standards, and advocated for engineering consistency. Expanding these efforts globally can help emerging markets overcome inefficiencies, reduce costs, and improve network reliability by adopting proven structural engineering frameworks such as ANSI/TIA-222.

The Mobile Infrastructure Engineering Consortium (MIEC): A Proven Model

The Mobile Infrastructure Engineering Consortium (MIEC) has demonstrated that collaboration among engineering firms, tower owners, and MNOs can yield significant efficiency gains and cost savings. With over $700 million in documented savings across 90,000 U.S. network projects, MIEC has proven the value of standardized structural analysis, data-driven decision-making, and streamlined engineering workflows. By expanding this model globally, telecommunications companies can drive similar benefits at scale.

Appendix A: Definitions

ANSI/TIA-222: A structural standard that defines requirements for antenna-supporting structures to ensure they meet the needs of modern communications systems in various environmental conditions like wind, snow, and ice.

Authority Having Jurisdiction (AHJ): An organization, office, or individual responsible for enforcing the requirements of a code or standard.

Changed Condition: Any change in equipment, scale, or geometry of the structure or the structure's principal purpose that results in a 5% change in the demand-capacity ratio.

Computational Fluid Dynamics: A computer-aided design technique that utilizes simulation and analysis to calculate the behavior of liquids or gases in and around the vicinity of a product.

Condition Assessment: The process of inspecting and evaluating the physical health of telecom structures to determine their safety, stability, and overall integrity.

Digital Twin: A virtual representation or simulation of a physical object, system, process, or environment that mirrors its real-world counterpart in real-time

Engineer of Record (EOR): A licensed professional engineer responsible for the engineering aspects of a project, including design, compliance with relevant codes and standards, and overall engineering integrity.

Installation Fault: An error or issue that occurs during the setup, construction, or installation of telecom infrastructure.

Large Language Model (LLM): A type of artificial intelligence (AI) model designed to process, understand, and generate human language.

Mapping / Structural Mapping: The process of documenting, analyzing, and visualizing the layout, condition, and attributes of telecom structures systematically.

Mount: A structural component used to attach or support telecom equipment, such as antennas, radios, or other communications hardware, to towers, poles, or other structures. The different types of Mounts are as follows:

- **T-Arm Mounts:** T-arm mounts are straightforward configurations typically installed on poles or other low-profile structures. Their simplicity offers easy maintenance and installation, but they require careful analysis to ensure stability under varying load conditions.
- **Sector Frames**
  - **V-Frames**: These provide robust support for multiple antennas and their supporting equipment and are typically designed for balanced load distribution.

- **T-Frames**: T-frames are similar to V-Frames but are designed for lighter, smaller antenna loads and have different load path considerations, often requiring precise structural mapping and analysis when larger, heavier loads are installed.

- **Platform Mounts:** These mounts accommodate equipment configurations like those of T-arms but also include design elements that provide ease of access and additional stability for the installation. They often introduce complexities in load distribution and interaction with the underlying tower structure due to their ability to typically support larger loading configurations than T-arms.

- **Non-penetrating ballast mount:** A mounting system that resists sliding and overturning moment entirely from the self-weight of its structural members, appurtenances, and mounting pipes. It is supplemented by adding weight to the attached mounting trays with ballast. Types of non-penetrating mounts include ballasted rectangular sleds and tripod mounts.[1]

- **Penetrating/anchored mount:** A mounting system positively attached to the underlying structure via weld, mechanical, or adhesive anchor. Its stability is derived through load transfer from anchored connections to the roof framing system or other building components. [1]

Mount Analysis: The process of evaluating and analyzing mounts' structural integrity, load capacity, and performance.

Mount Modification: The process of altering or adjusting a telecom mount's design, structure, or placement to accommodate a new equipment installation, modification, or any changed condition to a telecom structure.

Post-Installation Inspection (PII): The thorough inspection and assessment conducted after the installation of telecom infrastructure to ensure all components are correctly installed, meet design specifications, adhere to safety standards, and are fully functional.

Post-Modification Inspection (PMI): The thorough inspection and assessment conducted after modifications have been made to existing telecom infrastructure to ensure all components are correctly installed, meet design specifications, adhere to safety standards, and are fully functional.

Retrieval Augmented Generation (RAG): A machine learning technique used in natural language processing that combines retrieval-based and generation-based models.

Structural Failure: A telecom structure or component's collapse, deformation, or malfunction.

Appendix B: Examples of Quality Failures and Adverse Situations

Without a PMI process for every site installation, the MIEC has found that an MNO is likely to have quality failures and adverse situations in the field as often as 40% of the time across all sites. Examples are detailed and illustrated below.

Figure 5. Image and illustration where proposed mount modifications were not installed

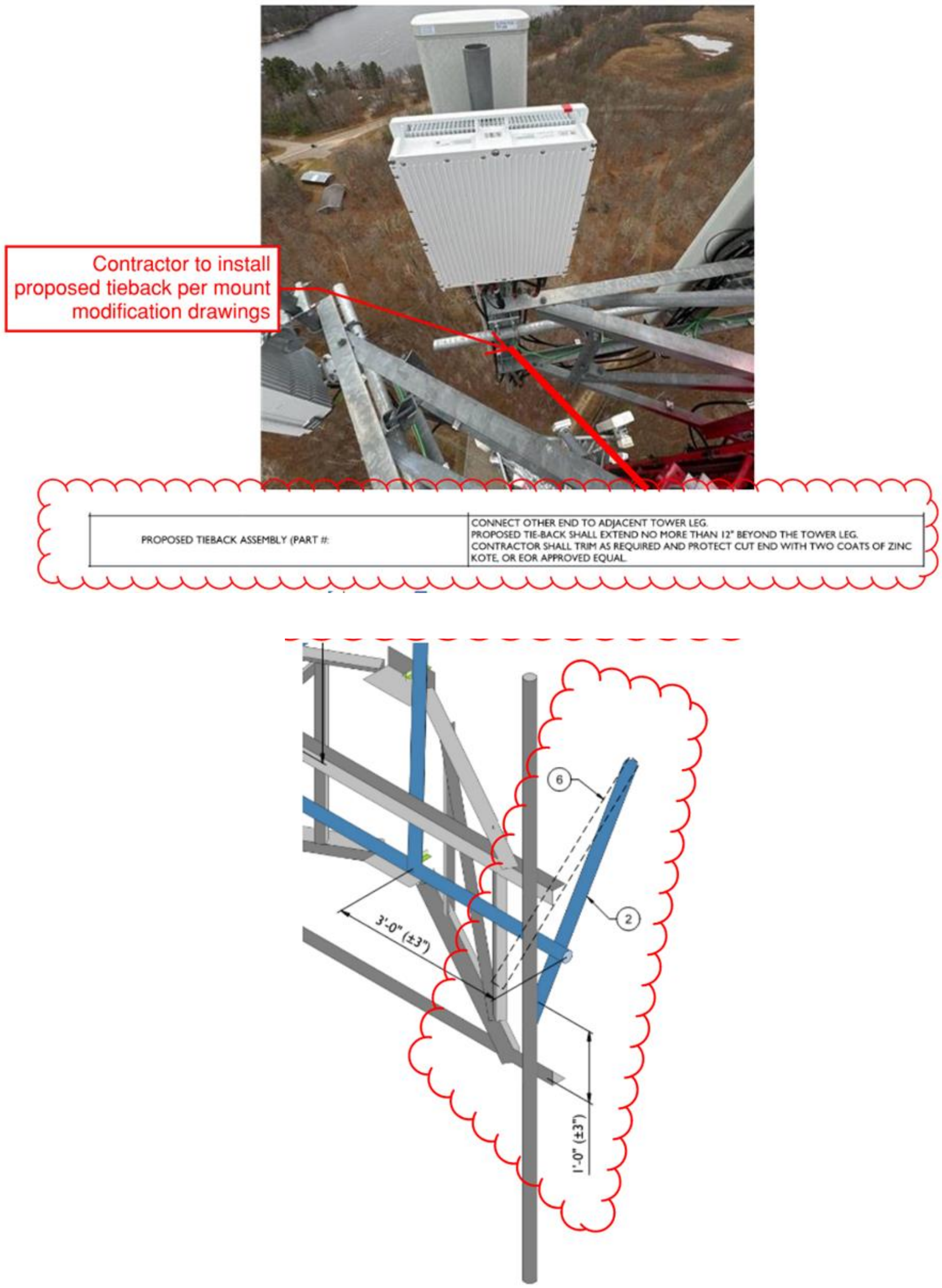


Figure 6. Illustration and image where mount modifications were not installed per the design (tower)

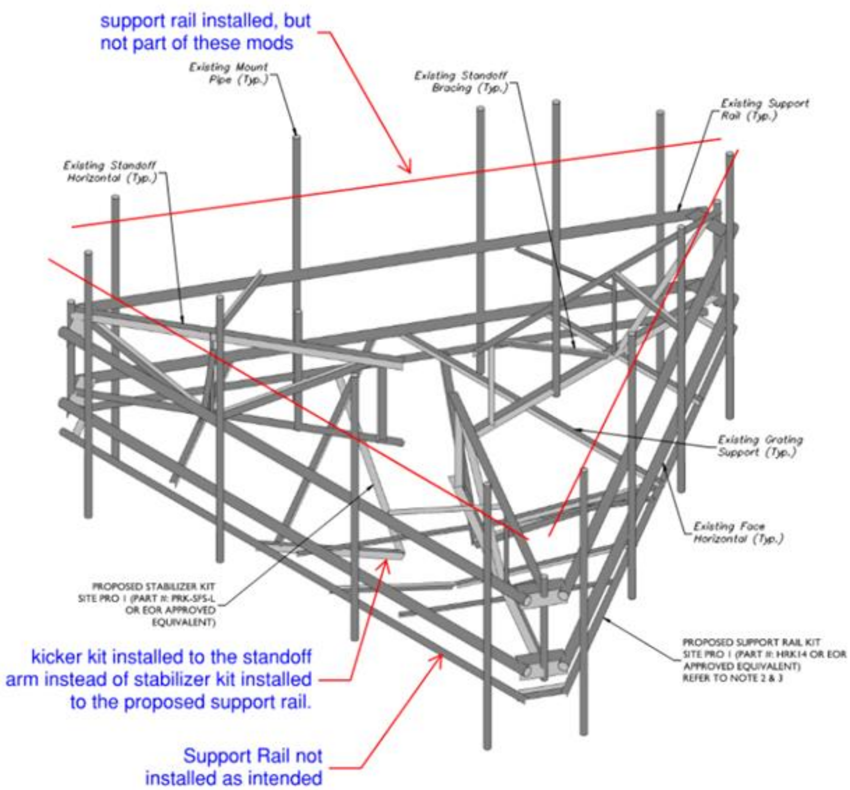
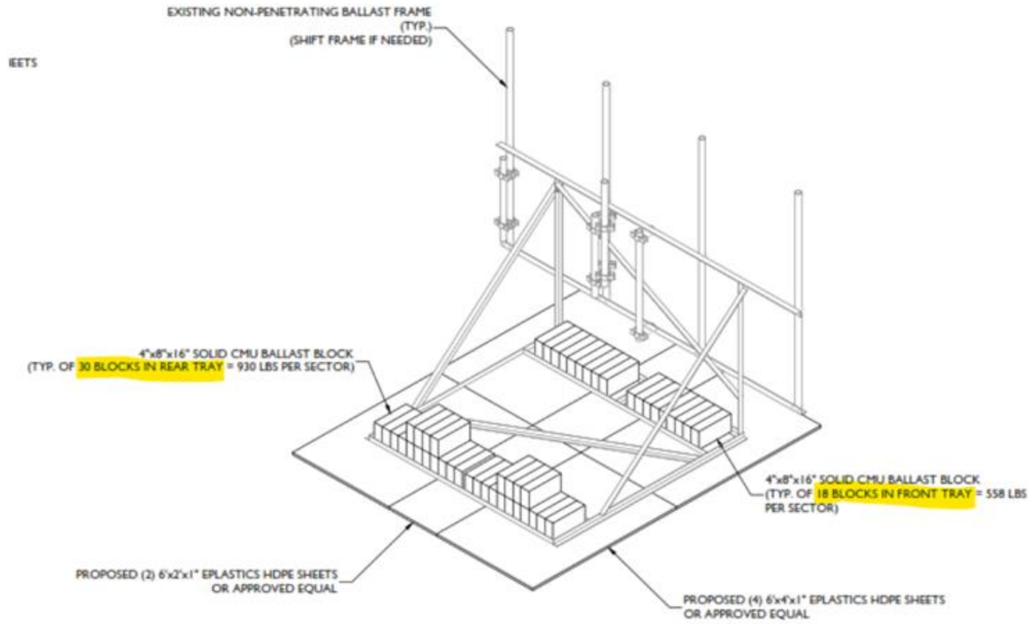


Figure 7. Illustration and image where mount modifications were not installed per the design (rooftop)

In this example, ballast was not removed per the design, resulting in ~3,780 lbs. of ballast per sled. This is significantly beyond what the underlying rooftop structure can handle (~930 lbs.).



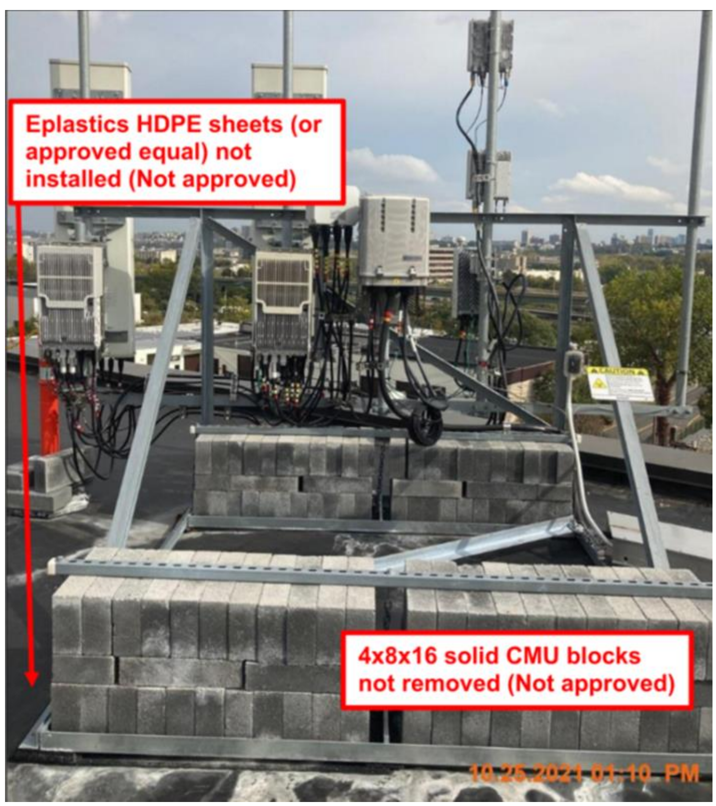


Figure 8. Image of antennas "cheated up" – centerline of antennas installed significantly above the centerline of the mount (~1.5'), impacting the structural capacity of the mount

Figure 9. Image showing tiebacks attached to tower bracing, which introduce significant forces into tower members that are not designed to handle them. Multiple tower owners have prohibited this practice. In the example shown below, over 1300 lbs of potential force may go through the tieback.

Figure 10. Image of existing or imminent damage to the safety climb or climbing facilities.

Figure 11. Images of mount components and/or equipment placed outside of the lease space. The photo on the left shows the mount initially installed with the new kicker kit. Because the kicker kit was not trimmed, it was installed ~3.5' below where it was proposed, putting the MNO tenant outside their contracted lease space. The photo on the right shows the final configuration after the EOR flagged the condition on a PMI and had the GC correct.

Figure 12. Image of mount components and/or equipment placement violates FAA requirements

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U.S. Patent Numbers: 9,546,497; 9,896,859; 9,926,716; 10,472,844; 10,781,601; 9,714,520; 10,538,935; 11,210,437; 11,359,399. Additional patents pending.

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