

Lessons Learned from the Arecibo Observatory Auxiliary M4N Socket Analysis and Implications for Future Observatory Designs

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ABSTRACT

The Arecibo Observatory collapsed after a progressive structural failure originating from a single open socket joint. A failure investigation was conducted to identify the cause of the first failed cable termination socket. Due to the nature of the suspended observatory receiver, the dominant source of loading in the suspension cables was due to deadload, with secondary contributions coming from environmental effects and observatory operation. The high ratio of deadload vs. live load applied to the cable over many years resulted in a creep failure mode of the cast zinc within the socket which further induced stress into the highly stressed wires at the entrance of the socket. The design of the socket joint did not explicitly consider socket constituent stress margins and time-dependent damage mechanisms such as creep. Lessons learned from this investigation led to recommendations for revising civil engineering cable standards, and recommendations for manufacturers and designers. The design of cables employing socket terminations should consider the cumulative damage effects from creep and cyclic loading, identify their corresponding worst-case inspectable defects, or establish a sufficiently high factor of safety so that the design is sufficiently robust to defects and time-dependent failure modes. The design should specify end-of-life capability and set service life inspection intervals with pass/fail inspection criteria. Finally, trial studies on design iterations were conducted to increase the reliability of cables with socket joints.

Keywords: Observatory, cable failure, socket design, creep, fatigue

1. BACKGROUND

1.1 Arecibo Radiotelescope Failure Event

The Arecibo Observatory is a radio astronomy, solar system radar, and atmospheric physics facility that was constructed in 1963 and periodically upgraded. In the 1990s, the structure underwent a major upgrade to include auxiliary main cables and extra backstay cables to increase the capability of the feed platform to support a much larger instrument and suspended platform structure called the Gregorian Dome. The observatory structural elements consist of three towers spaced 120 degrees apart that supported main, auxiliary, and backstay cables to keep the receiver platform and instrument supported and controlled with extreme precision. After the upgrades in the 1990s, each tower received another pair of 3.25-inch auxiliary main cables and two additional 3.625-inch backstay cables to support the upgraded mass. An open spelter socket termination was used on the tower end of the cable, while slightly different termination types were used on the feed platform side.

In the middle of the night on August 10, 2020, an auxiliary main cable (denoted Aux M4N) failed and pulled free from the North side of Tower 4 during normal observatory operations. On November 6, 2020, one of the four original main cables of Tower 4 failed. This second cable failure differed from the Aux M4N failure in that it was one of the original main cables, which employed a different structural strand construction and a different cable termination type. On

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December 1, 2020, a second original main cable failed, causing a chain reaction of failures and load imbalances in the observatory suspension cable system that led to the total collapse of the observatory and supporting tower segments.

1.2 Key Finding of the NASA Investigation

NASA was asked by the University of Central Florida (UCF), the organization managing Arecibo on behalf of the National Science Foundation (NSF), to support the investigation into the Arecibo Observatory auxiliary cable failure. Efforts included technical support, independent forensics and failure analysis of the Auxiliary Main (Aux M4N) socket, independent modeling of the socket, materials testing, and fishbone analysis to determine the most probable contributors and failure scenario. The overall effort was a collaboration between the NASA Engineering and Safety Center (NESC), Kennedy Space Center (KSC), Marshall Space Flight Center (MSFC), and The Aerospace Corporation. The primary objectives were to support the NSF's investigation and provide an independent assessment of any systemic concerns that could impact NASA or the broader engineering community [1].

The investigation consisted of root cause analysis, forensic investigation of the Aux M4N socket joint, and structural finite element simulation of the joint, Figure 1. The integrated team evaluated all available investigation data through cause-and-effect analysis and developed a most probable failure scenario of the Aux M4N cable failure. Forensic data and observations were evaluated in combination with structural modeling and materials testing.

The NASA Engineering Safety Center and The Aerospace Corporation concluded that the most probable cause of the Aux M4N cable failure was a socket joint design with insufficient design criteria that did not explicitly consider socket constituent stress margins or time-dependent damage mechanisms. The socket attachment design was found to have an initially low structural margin, notably in the outer socket wires, which degraded primarily due to zinc creep effects that were activated by long-term sustained loading and exacerbated by cyclic loading. Additionally, a few wires showed evidence of hydrogen-assisted cracking (HAC) and wire surface defects that may have contributed to initial outer wire failures.

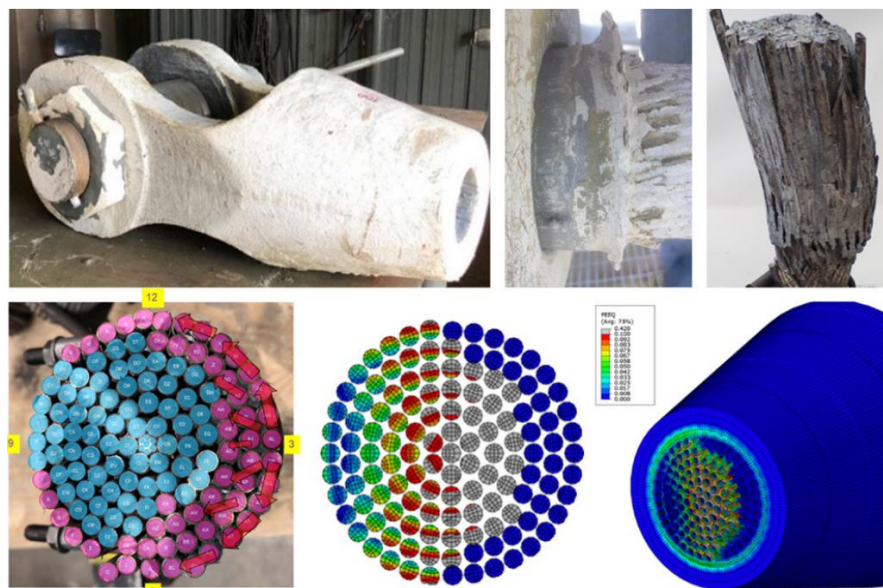


Figure 1. NASA Investigation of failed Arecibo Aux M4N cable. Top: socket (left); zinc extrusion (center); pulled out cable (right). Bottom: forensic and finite element model recreation of M4N failure progression.

1.3 Open Spelter Socket Joint

Zinc spelter socket joints are terminations in stay cables used throughout industry that transfer loads between adjacent structures. This type of open spelter socket joint is extensively used in structural applications because it is highly efficient and reliable. The open zinc spelter socket joint was used in the Aux M4N cable, which is the cable that failed and instigated the chain of events leading to the collapse of the Observatory. The cable failed near the joint where the cable connects with the open spelter socket, Figure 2(a). Aux M4N structural strand follows a 1×127 construction and consists of 126 individual 0.25-inch diameter wires wrapped around a single, seven-wire strand in six concentric rings with a pattern of 6, 12, 18, 24, 30, and 36 wires. Terminations consist of stay cable wires that are unraveled, broomed, and then embedded/bonded into a zinc casting inside a conical volume. Cable tension wedges the zinc material against the slanted conical surface, which then develops a large compression zone within the zinc such that if a failure were to occur it is expected to be outside the socket joint in the cable span.

Cable tensions from observatory dead load, operational loads, and survival transients are transmitted to the socket termination through the 126 individually broomed wires that are held in place by the cast zinc spelter within the steel open socket conical volume, Figure 2. The zinc that fills the socket cavity is bonded to the wires, and this bond creates an efficient load transfer among the wires within the socket. A special characteristic of the zinc spelter socket termination is that the combination of zinc plasticity and the conical volume forces a “squeezing” effect to occur around the broomed wire bundle in the narrow part of the socket. The high confining pressures experienced at the outlet of the socket keep the broomed wires from pulling out of the zinc and allow the failure to occur in the cable outside the socket, thus realizing the cables’ full structural capability, otherwise referred to as a 100% efficiency termination.

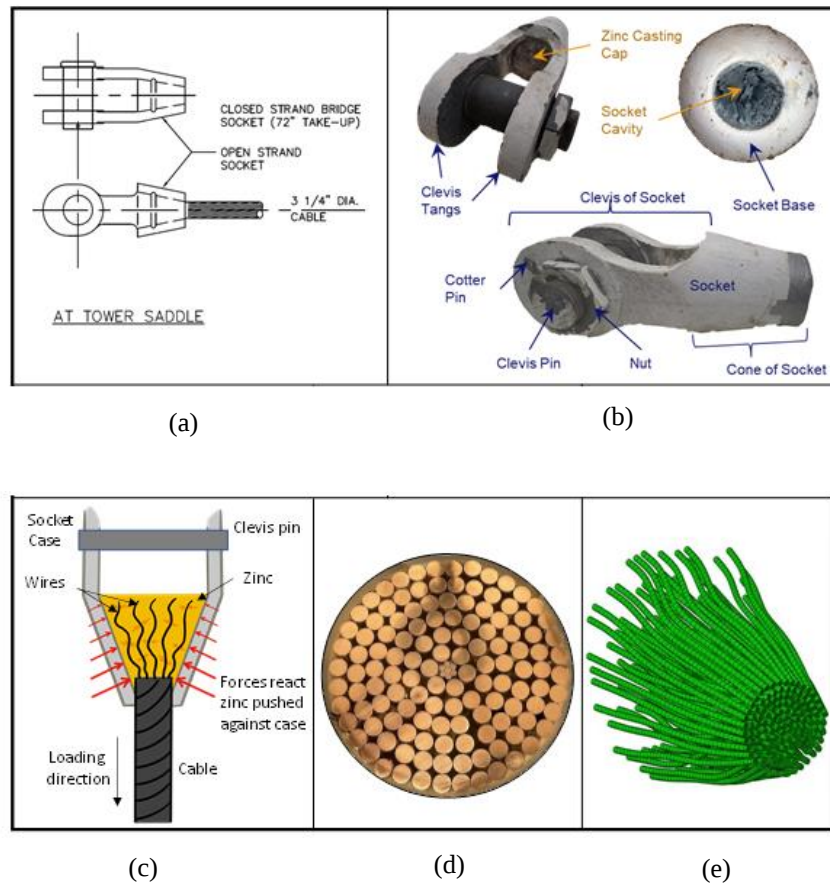


Figure 2. (a) Open spelter socket drawing, (b) socket terminology, (c) Aux M4N broomed wire reconstruction, (d) 1×127 structural strand cross section, and (e) cable-socket interface detail sketch.

1.4 Objectives

Industry recommendations (Section 2) for revising civil engineering cable standards, and recommendations for manufacturers and designers are presented based on key findings of the NASA investigation. New proposed design trades of socket joints and evaluations of these designs will be presented in Section 3. The overall goal of this two-prong approach is to improve industry standards and to improve the design of the socket joints.

2. INDUSTRY RECOMMENDATIONS

In the Arecibo observatory failure, a combination of low design margin at the socket termination and a high percentage of sustained loading revealed an unexpected vulnerability to zinc creep and environments, resulting in long-term cumulative damage and progressive zinc/wire failure. The resulting core-pullout failure mode that preceded observatory collapse was found to be (1) unique compared with other industry applications, (2) insufficiently addressed within existing standards, and (3) a potential risk for similar designs.

In-service inspections showed evidence of progressive zinc extrusion on several Arecibo sockets which, in hindsight, indicated that an appreciable amount of damage had accumulated within the socket. However, the design did not contain set service-life inspection intervals with pass/fail inspection criteria, nor did it specify an end-of-life capability requirement associated with service life degradation, and the sockets remained in-service as the evidence was not tied to an understanding of need for action.

Recommendations are proposed to prevent failures of similar socket joints. Lessons learned can be incorporated in the revision of civil engineering cable standards or in design best practices. Generally, the design of cables employing socket joints should ensure positive margins for the various constituents of the socket joint. The design should also consider the cumulative damage effects from creep and cyclic loading and consider worse-case defects traceable to inspections or establish a sufficiently high factor of safety so that the design is sufficiently robust to defects and time-dependent failure modes. The design should specify end-of-life capability and set service life inspection intervals with pass/fail inspection criteria.

2.1 Governing ASCE Cable Standards

ASCE/SEI 19-22 “Structural Applications of Steel Cables for Buildings” [2] replaces ASCE Standard 19-16 [3], and it is an expanded and revised version of ASCE 19-16. This standard provides requirements for the structural design for use as static structural elements for the support and bracing of buildings and other cable-supported structures.

The cable standard ASCE 19 was originally published in 1966 and was developed for structural applications of steel cables for buildings and was published by the American Iron and Steel Institute (AISI). Later publications include “Design Fundamentals of Cable Roof Structures” published by AISI in 1969 [4]; “Cable-Suspended Roof Construction State-of-the-Art” in the Journal of the Structural Division, ASCE, 1971 [5]; and the Manual for Structural Applications of Steel Cables for Buildings, AISI, 1973 [6]. Since then, the standard continued to be revised to incorporate industry lessons learned and recommendations. Prior editions of the ASCE/SEI 19-22 include ASCE 19-96, ASCE/SEI 19-10 [7], and ASCE/SEI 19-16.

A review of these standards was conducted, and recommendations were developed considering the Arecibo observatory investigation findings.

2.2 Consideration of the Environments

Temperature changes can cause fluctuating loads in the cables and affect the mechanical performance of the constituent materials of the cable assembly, particularly the constituents within the socket termination. Higher temperature exposure can reduce strength capability of these joints. Cold temperature exposure can cause embrittlement of the constituent materials and cause the joint to have less ductility and consequently, less load redistribution. The design should account for changes to the mechanical and physical properties of cables and end fittings when these joints are subjected to temperature extremes. The characterization of these properties can be accomplished by coupon or subscale tests that are environmentally conditioned to the in-service predicted temperature extremes.

2.3 Fatigue

Fluctuating loads in the cable can be caused by temperature fluctuations, vibrations from winds, rain, or earthquakes, and from operational use. Conceptually, every cycle experienced by the cable during service decreases cable strength capability over time. Consequently, cable fatigue life should be evaluated to ensure robustness to fatigue environments. When designing the cable, the effect of mean load and load configuration should be accounted for in the fatigue assessment. An effective approach to achieving “infinite” life in the cable constituents is to use an endurance diagram. When the mean stress is non-zero, the Goodman diagram developed by plotting the alternating stress in the vertical axis, and the mean stress in the horizontal axis. A straight line is drawn between the material's endurance limit on the vertical axis, and the ultimate tensile strength on the horizontal axis. A point in this diagram represents the operational conditions of the socket, and if it lies below the line then the material is unlikely to fail during the lifetime of the cable. Otherwise, the socket joint will have a finite life. In these cases, full-scale fatigue testing can be accomplished by subjecting the socket joint to cyclic loading. Because the socket joint will see millions of cycles from different sources of loading, Miner's rule or an alternate cumulative damage approach can be used to formulate a test program where an equivalent fatigue damage is induced by testing the socket joint to larger amplitude loading and a smaller number of cycles.

2.4 Creep

Long-term sustained loading conditions can cause the cable to gradually elongate over time and cause the material within the socket to degrade. The design of cable components should account for creep, which depends both on applied stress and temperature. In the Arecibo failure investigation, zinc creep was one of the primary failure mechanisms, which was activated by a high percentage of sustained (dead) load and a design factor of safety of approximately 2.0 on ultimate strength. This visually manifested as zinc extrusion from the socket and was shown to further reduce structural capability of the individual wires comprising the cable at the socket termination.

The effect of temperature is evaluated based on the percentage of a structural material's absolute melting temperature, T_m , in Kelvin. Under sufficiently high sustained loads, creep in typical metallic components becomes a concern at temperatures as low as $0.4 \times T_m$. For commercially pure zinc used in zinc spelter socket terminations, room temperature (roughly 70°F) is above the $0.4 \times T_m$ homologous temperature and demonstrates susceptibility to creep. This is not the case for the cast steel socket or the steel wires comprising the cable because their homologous temperature at ambient air conditions is much less than $0.4 \times T_m$. The susceptibility for the creep failure mode depends on service temperature range, stress level, duration of stress applied, and which phase of the creep process the material is experiencing.

Since creep is challenging to predict and to test, socket joints can be designed to preclude creep failure modes by material selection or inspections can be instituted over the life of the socket joint to that would trigger a repair. Otherwise, significant efforts are required to develop high-confidence predictive creep models that are anchored to sub-element testing. Full-scale tests could be impractical to formulate as they would need to be conducted in a short period of time but need to simulate long-service lives.

2.5 Cumulative Damage

The design of end fittings should meet fatigue and creep life requirements and consider the cumulative damage combination of fatigue and creep failure modes. Generally, materials incur cumulative damage due to both sustained and cyclic loading, as structures are not likely operating in conditions where one of the contributors is totally absent. Accumulation of damage occurring due to sustained and cyclic loading can be linearly combined using Miner's rule. This is illustrated by the interaction diagram in Figure 3. Here, n and N_d are the number of cycles and the allowable number of cycles for the j -th loading condition; t and T_d are the actual time at stress level k and the allowable time at that stress level. D is the allowable combined damage fraction. The point of this diagram is simply to illustrate that time-dependent degradation modes are not only due to sustained loading alone, but that cyclic loading can accelerate creep-related failure modes. The graphic shows an example exchange rate between cyclic and time-dependent contributors to total accumulated damage.

The individual failed wires in the Arecibo Aux M4N cable did not reveal any evidence of fatigue from the microstructural forensic studies that were conducted. The large-sustained loading (compared to other fluctuating loads) resulted primarily in creep of the zinc which, in turn, progressively transferred load into the outer cable wires, eventually overloading the wires one-by-one until the net section of zinc gave way to pull the cable from the socket. Fluctuating loads from observatory motion, winds, earthquakes, and temperature fluctuations likely added additional damage into the

socket joint until failure occurred. The combination of mechanisms should be accounted for in the design of cable supported structures.

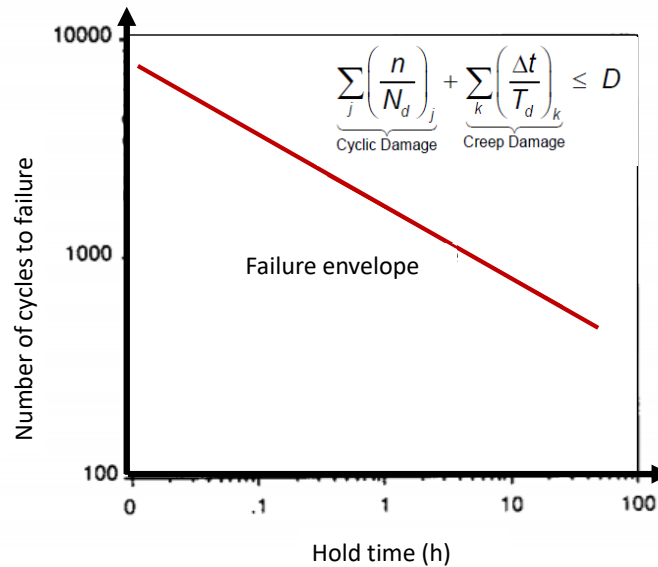


Figure 3. Cumulative damage in materials can be due to a combination of creep and fatigue. An equivalent damage index such as the one in Miner's rule can be used as a design tool to assess failure.

2.6 Design Practices

Based on the lessons learned from the Arecibo failure investigation, there are six desirable design and test practices for these socket joints:

1. Keeping the failure away from the joint by designing the socket joint to be stronger than the cable improves design reliability by ensuring a repetitive failure mode and increasing certainty in the capability of the design. The strength of these socket joints is not easily predictable and can be affected by workmanship quality. The location of failure during test of these socket joints tends to vary from just outside the termination to near mid-span of the cable.
2. Consider a sufficiently high design factor of safety to preclude difficult-to-predict failure mechanisms such as creep and fatigue. Analysis methods may not be able to predict the design capacity of these socket joints, due to the complexity in failure modes. In aerospace applications, a factor of safety of near 4.0 on strength and a proof factor of 1.5 over the maximum predicted load in service has been shown to result in robust fatigue life.
3. Ideally, the qualification test should include worst-case manufacturing imperfections that validate accept/reject defect criteria. These defect acceptance criteria can be used for post-fabrication screening, post-proof inspections, and in-service maintenance inspections.
4. While ASCE 19 standards allude to redundancy, this design practice is a key element in ensuring that the structural system is robust to local cable failures. The Arecibo radiotelescope cable failure led to other cables failing until ultimate collapse of the system. ASCE/SEI 7-16 requires that buildings be designed to be robust to local damage. For example, the building should not collapse if any column fails. Analogously, a cable structure should not collapse if one local element of the cable system is damaged, regardless of the cause.
5. If most of the total cable load is due to deadloads and the socket joint is designed to a factor of safety of 2.0, then the designer of spelter sockets should consider creep as a viable failure mode. This is of particular importance given the

susceptibility of zinc to creep and the effects that zinc plasticity has on the wire stress levels. In Section 3, a design is presented that could suppress creep failure mode.

6. Keep positive structural margins for each of the cable assembly constituents. In the Arecibo failure investigation, finite element analysis and forensic investigation of an open conical zinc spelter socket with 1×127 cable strand showed that at half of the cable breaking load, the stress distribution across wires was nonuniform and that the outer wires stresses were near ultimate strength but with residual elongation capability. Designing the socket joint or designing the system so that the maximum load applied to the cable results in positive structural margins for each failure mode within the socket joint increases design reliability. Traditionally, design/build verification methodologies for similar socket terminations did not consider constituent stresses and localized stress concentrations in demonstrating positive structural margins; consequently, these socket terminations may have been vulnerable to time-dependent cumulative damage from fatigue and creep.

2.7 Post-Fabrication Non-destructive Inspections (Pre-Proof)

Socket joints should be examined for defects, as the fabrication of these joints are labor-intensive and prone to workmanship defects. These defects can be initiation points for failure in-service. Manufacturing defects can result in reduced strength capacity of the cable assembly. Nondestructive testing (NDT) techniques should be developed and validated to inspect for defects in these joints. Type of defects include voids, porosity, or crack-like indications. NDT procedures include magnetic particle, dye penetrant, ultrasonics, and radiography such as radiographic film recording and computed radiography. These methods are more reliable in regions of less geometric and design complexity. The size and characteristics of defects that are acceptable should be defined for each type of defect, because a larger defect can be tolerated in a low-stressed region compared to highly stressed region.

2.8 Proof Test and Post-Proof NDT

Because the fabrication is inherently manual and workmanship sensitive, socket terminations commonly receive a proof test load as a workmanship screen to ensure adequate bond strength developed between the zinc and broomed wires and to seat the constituents within the conical socket. The proof load level can be specified by the customer as a percentage of rated breaking strength or some proportion of design load. A proof test to 50% of the rated breaking strength is a common target load value. In conclusion, assemblies proof tested to a tension force greater than the load in service can serve as a good quality control test.

The proof test is a gross workmanship screen, acts as a screen for “early failures,” but does not act as a screen for wear out failure modes such as fatigue. However, a sufficiently high proof factor (~1.5) and ultimate load factor (>2.5) can lead to robust designs against fatigue due to the inherently low in-service stresses that result from adhering to higher ultimate factors of safety. A socket-joint build that passes a proof test load much larger than the in-service load will also be more robust to defects during service. This concept is used in aerospace structural systems where inspection techniques are difficult to implement, and fatigue is challenging to assess.

A post-proof NDT should be conducted following the proof test to ensure any “weak” areas within the joint did not progress into damage greater than the acceptable defect size. This is consistent to aerospace applications, where a post-proof NDT is conducted in workmanship sensitive regions such as bonded joints.

Another inspection that should be conducted is measuring the amount of deflection of the zinc spelter within the socket. The zinc spelter will normally exhibit a small displacement of the zinc cone when seating into the socket during the proof test. This is observed where the cable exits the socket by comparing the positioning of the zinc at the socket base before and after the proof test. This displacement is a normal result of socket loading, and unless excessive, is not an indication of poor workmanship or design. A pass/fail displacement criterion should be developed and used after the proof test to assess the adequacy of the measured displacement.

2.9 Maintenance

Inspection requirements and requirements for cable repairs should be established as part of the structural design of the cable assembly. Design documents should specify the type of nondestructive tests, frequency of testing, and acceptance criteria for each type of defect.

Because the fabrication is inherently manual and workmanship sensitive, socket terminations may be subject to deterioration from in-service conditions. Structural cable assembly elements should be inspected during the planned

service of the cable, ideally using the validated NDT. NDT can be especially useful in inaccessible areas to visual inspections. Inspections should measure material extrusion from socketed termination because detected extrusion could indicate to potential detrimental mechanisms occurring within the socket. The inspections should be accompanied by a accept/reject criterion, which could trigger a replacement or repair. Accept/reject criterion should be defined or justified by analyses or tests. ASCE 19 standards require a six-year cycle inspection interval, but additional intermediate inspections should be considered depending on the design and severity of the loads and expected environments.

The industry should develop inspection techniques capable of finding internal damage even if there is any clear external indication of damage. In the Arecibo failure event, forensic investigation found internal damage due to environmental conditions, which in combination with wire defects may have further degraded capacity of the socket joint without clear external indication.

In the Arecibo radiotelescope collapse, the cable failure was induced by cumulative damage from creep-dominated failure mode enhanced by cyclic loading. The zinc spelter was progressively extruding from the socket over time and regular inspections of the amount of extrusion could have indicated potential issues that would have triggered the cable requiring replacement or reinforcements.

3. DESIGN TRADE STUDIES

Open socket joints are effective because of the large confining pressure that forms within the zinc and acts around the broomed wire bundle in the narrow part of the socket. The high confining pressures keep the broomed wires from pulling out of the zinc and allow the failure to occur in the cable outside the socket. However, the design allows the zinc to extrude from the socket over time and the outer wire stresses are significant.

A good design would ensure that the highest wire stresses within the cable occur outside of the socket joint so that the failure mode is repeatable, and that zinc extrusion is reduced or eliminated.

3.1 Design Trade Studies

Five design concepts models were considered for examination and are illustrated in Figure 4: (1) Conical socket geometry with no wire-outlet lip; (2) Conical socket geometry with sharp corner wire-outlet lip; (3) Conical socket geometry with rounded corner wire-outlet lip; (4) Conical socket geometry with retaining mesh plate sitting against rounded wire-outlet lip. The retainer mesh plate has holes where the individual wires pass-through. Note that, for clarity, the zinc is not shown to emphasize the retaining plate design; and (5) Doubly curved socket geometry with large-rounded corner wire-outlet lip. Model 2, Figure 4, is the baseline model most representative of the Arecibo socket joint that had failed.

3.2 Finite Element Models

Finite element analysis was conducted to examine the effects of socket geometry on critical stress characteristics of the socket termination constituents. A finite element model in full three-dimensional fidelity of each design trade was developed in the software Abaqus. A representative model is shown in Figure 5. On the left of the figure, all the major features are illustrated, and on the right side, an example mesh refinement is shown for wires and zinc without the outer socket.

Several analytical studies found that the presence of the actual clevis joint of the socket did not affect the internal stresses developing in the wires and zinc. Therefore, in all trade studies, the representation of the socket was simplified to the conical outer shape and the appropriate inner geometry which restrains the zinc. The baseline set of mechanical properties are provided in Table 1.

The nonlinear stress strain curved used for the individual wires comprising the cable was generated by Ramberg-Osgood relations to match available test data and is shown graphically in Figure 6. Commercially pure zinc is a unique structural material in structural socket terminations because its tensile capability is extremely low; however, its compressive capability is high. Grain sizes also vary significantly based on manufacturing method and rate of cooling during casting. As such, it is difficult to construct a high-confidence material model that accurately reflects both tension and compression response or when attempting to model progressive damage. However, a representative nonlinear zinc material curve was used in the analyses, and it is shown graphical in Figure 7.

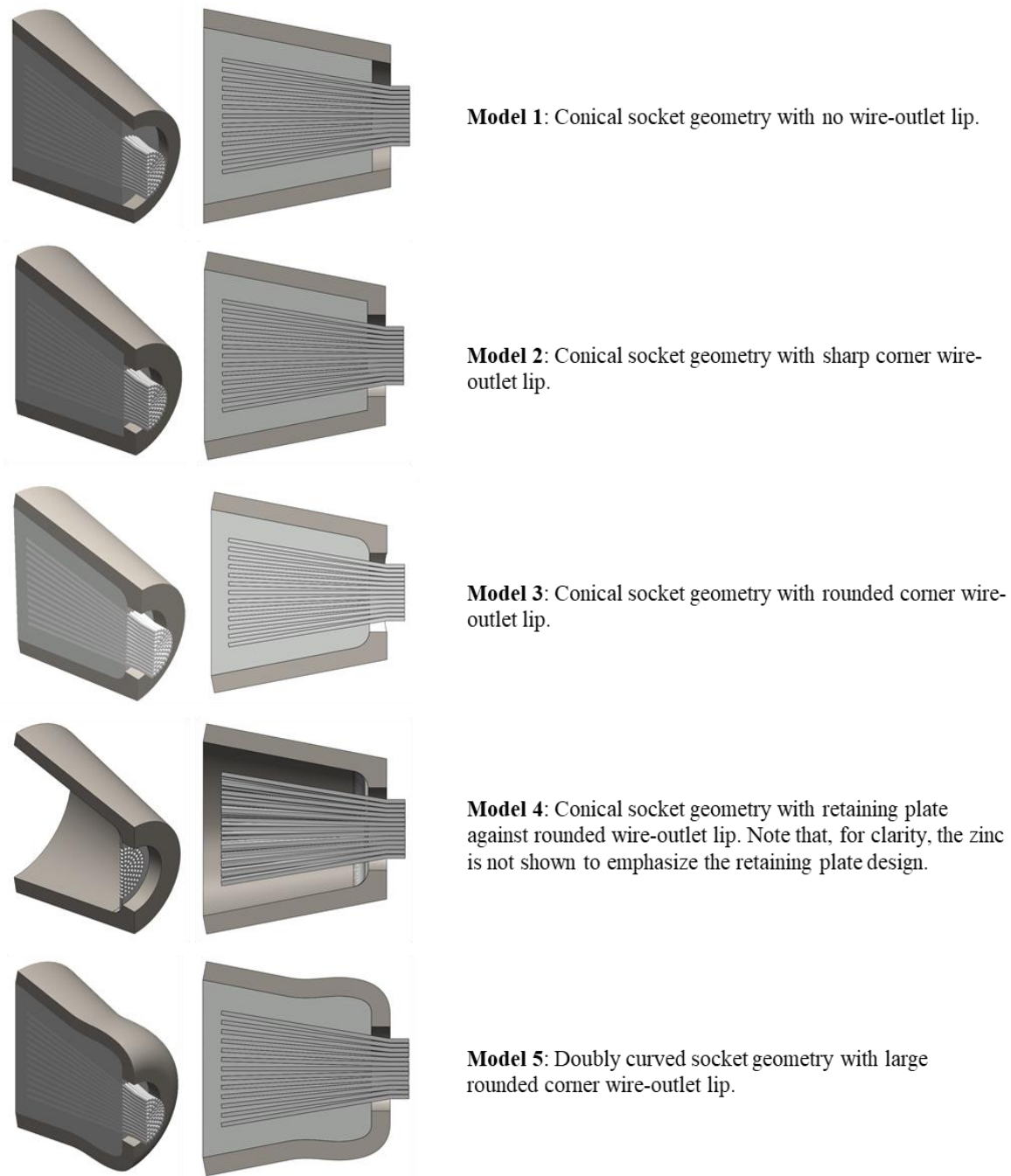


Figure 4. Isometric view, section view, and descriptions for the five model design concepts considered in this study

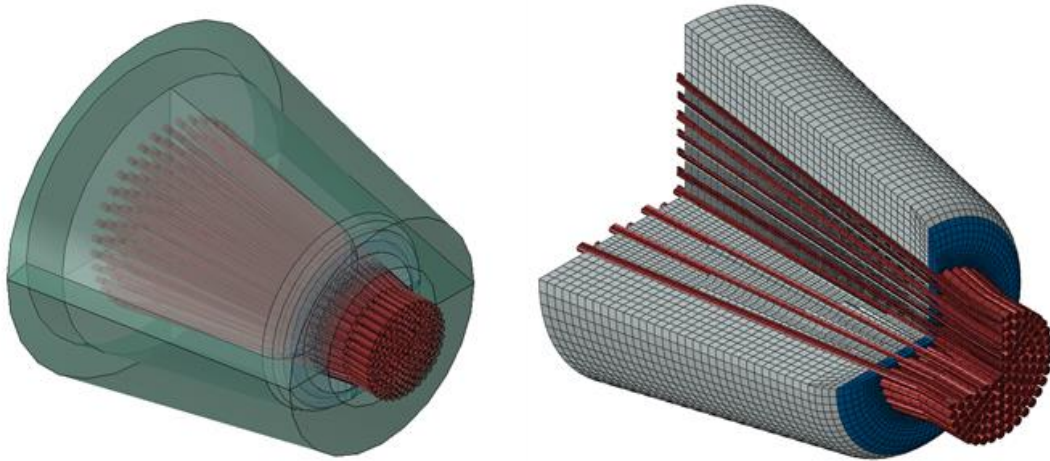


Figure 5. Model geometry isometric view and section cut view to show mesh density and refinement

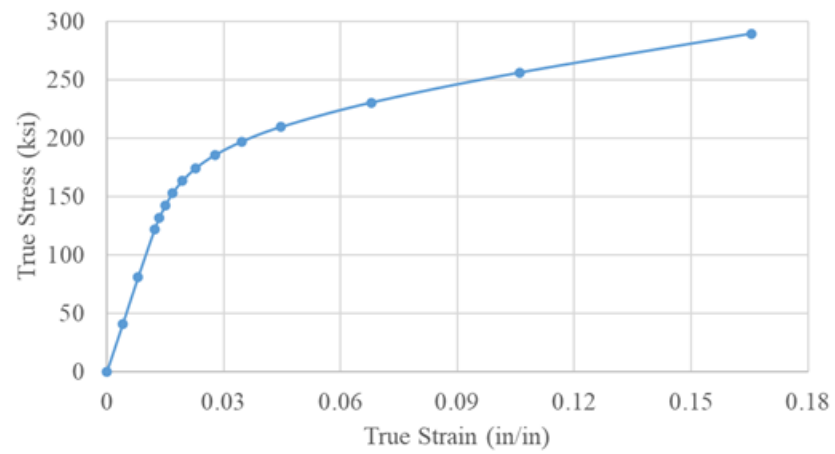


Figure 6. Stress-strain curve of A586-1 steel wire

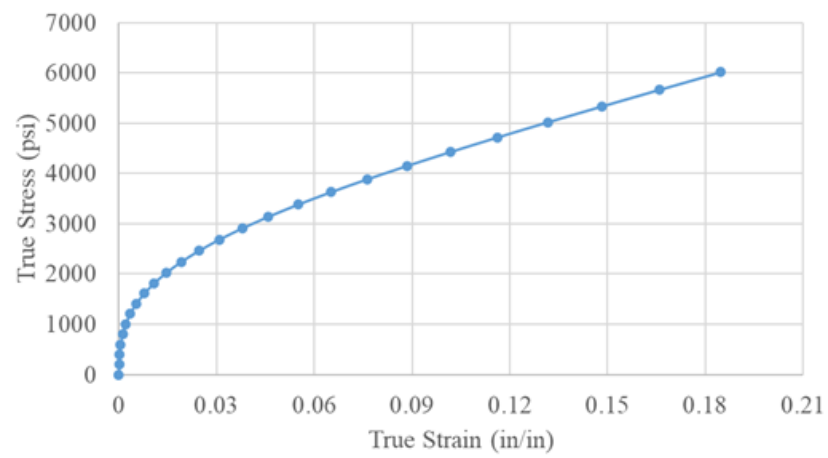


Figure 7. Stress-strain curve of commercially pure zinc

Table 1. Mechanical properties for the various cable assembly constituents.

Cast Steel Socket (A148 Grade 90-60 Cast Steel)	Commercially Pure Zinc	Structural Strand Wires (A586-91 Steel Cable)
Elastic Modulus: 27 Msi	Elastic Modulus: 14 Msi	Elastic Modulus: 23 Msi
Poisson's Ratio: 0.29	Poisson's Ratio: 0.25	Poisson's Ratio: 0.29
Yield Strength: ~70 ksi,		Yield Strength: 150 ksi
Ultimate Strength: ~100 ksi	Ultimate Strength: < 10 ksi	Ultimate Strength: >220 ksi (min spec)

3.3 Design Trade Parameters

For a given set of reasonable material properties, the various design concepts were compared with particular emphasis on the effects of socket geometry on the zinc and wire stresses. Extensive studies during the failure investigation [1] found that the major failure modes in consideration for such designs involve individual wire stresses, location of peak confining pressure in zinc, and plastic strain of the zinc spelter. As such, the various design concepts can be compared to each other according to wire stress, confining pressure, and zinc plastic strain to better develop and understanding of design sensitivities and qualitatively assess potential for design improvement. Figure 8 shows a comparison of yield stress indices for each of the five respective designs while Figure 9 shows a comparison of non-dimensional zinc confining pressure stresses, and finally Figure 10 shows a comparison of zinc plastic strain for each design.

A qualitative system was established to rank the design concepts with respect to each other based on the critical stress parameters. The intent of the ranking is not to ascertain whether a design is acceptable or unacceptable, but rather to identify sensitivities to certain design parameters and explore any opportunity for improvement in the design space. Figure 11 shows the consolidated rankings for Models 1 through 5. Models 3 and 4 are the most favorable of the designs considered. The colored squares register the ranking from left to right in accordance with the columns of values being examined (wire stresses, confining stress, and plastic strain).

The ranking of the various design subtleties was based on extensive studies on representative socket design for 1x127 structural strand to material property variabilities, voids, repeated loading, individual wire brooming, modeling simplifications, and damage progression. Throughout the complete body of analysis trade studies, it was learned that a good socket design is one where the cable develops complete strength while a net section cable failure occurs outside the socket joint. Further, the time-dependent failure modes such as creep and fatigue are nearly impossible to detect if the critical regions of stress are not accessible for visual inspection or apparent from the outside of the joint. As such, it is qualitatively more desirable to have (1) critical stresses in the wires be outside the socket termination, (2) low magnitude of plastic strain bands in the zinc to minimize the occurrence and rates of zinc creep, and (3) high confining pressure on the wires nearest to the wire outlet from the socket to constrain the wires from slipping and create a locally expected location for failure at the socket.

It is noted that the cone-only socket which does not contain any geometric lip feature at the wire outlet is generally the worst performer across all three categories. The sockets containing geometric lip features, whether as a corner, round, or with a double-curved socket housing all show improved confining pressure distributions and plastic strain contours compared to the pure conical socket. The least conventional of them all, Model 4, leverages a retaining plate that is stiffer material (akin to steel) at the retaining lip which prevents the gross plastic flow of zinc and concentrates confining pressure and stresses in the wire near the outlet of the socket. It is hypothesized that this type of feature may enable more repeatable static and time-dependent failure modes of zinc spelter socket termination designs. At minimum, this study has shown that the design trade space for geometric socket feature variability could be further explored to achieve higher performance or improved reliability of spelter socket termination designs.

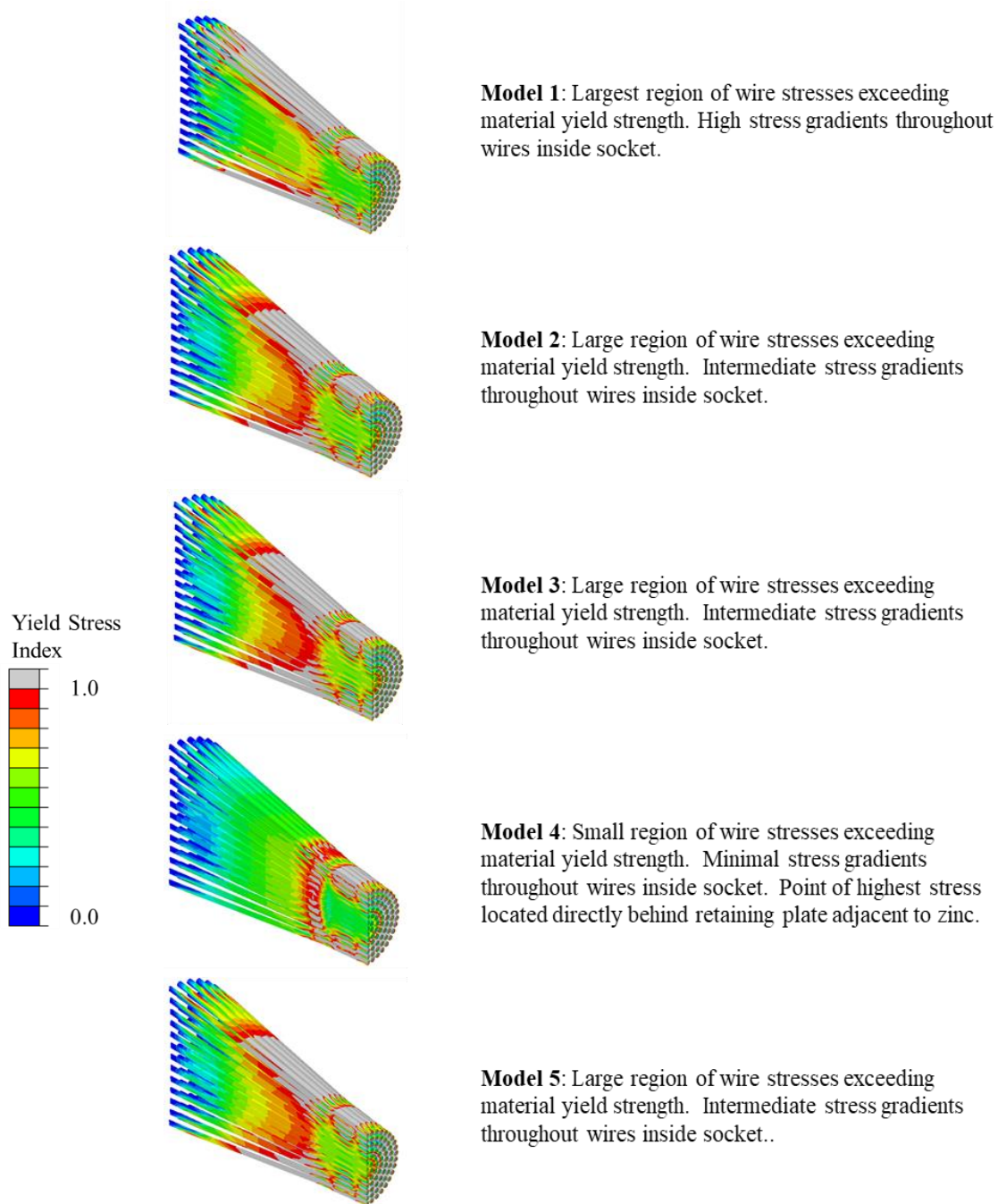


Figure 8. Stress indices for each design concept showing variable peak stress locations and gradients

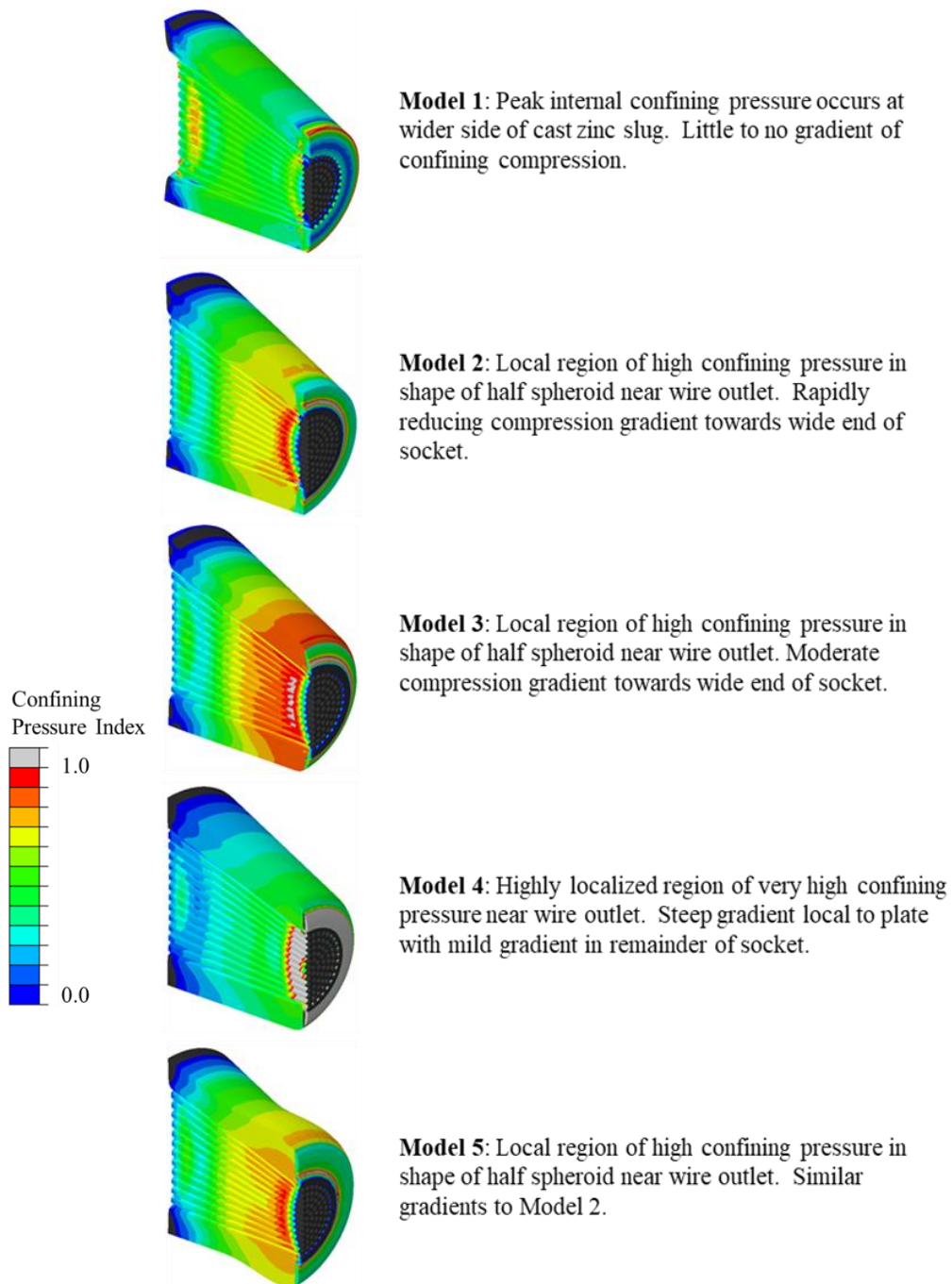


Figure 9. Confining compressive stress in cast zinc slug shown for each of the model configurations. High values indicate large amount of triaxial compression and good retention of zinc onto embedded wires.

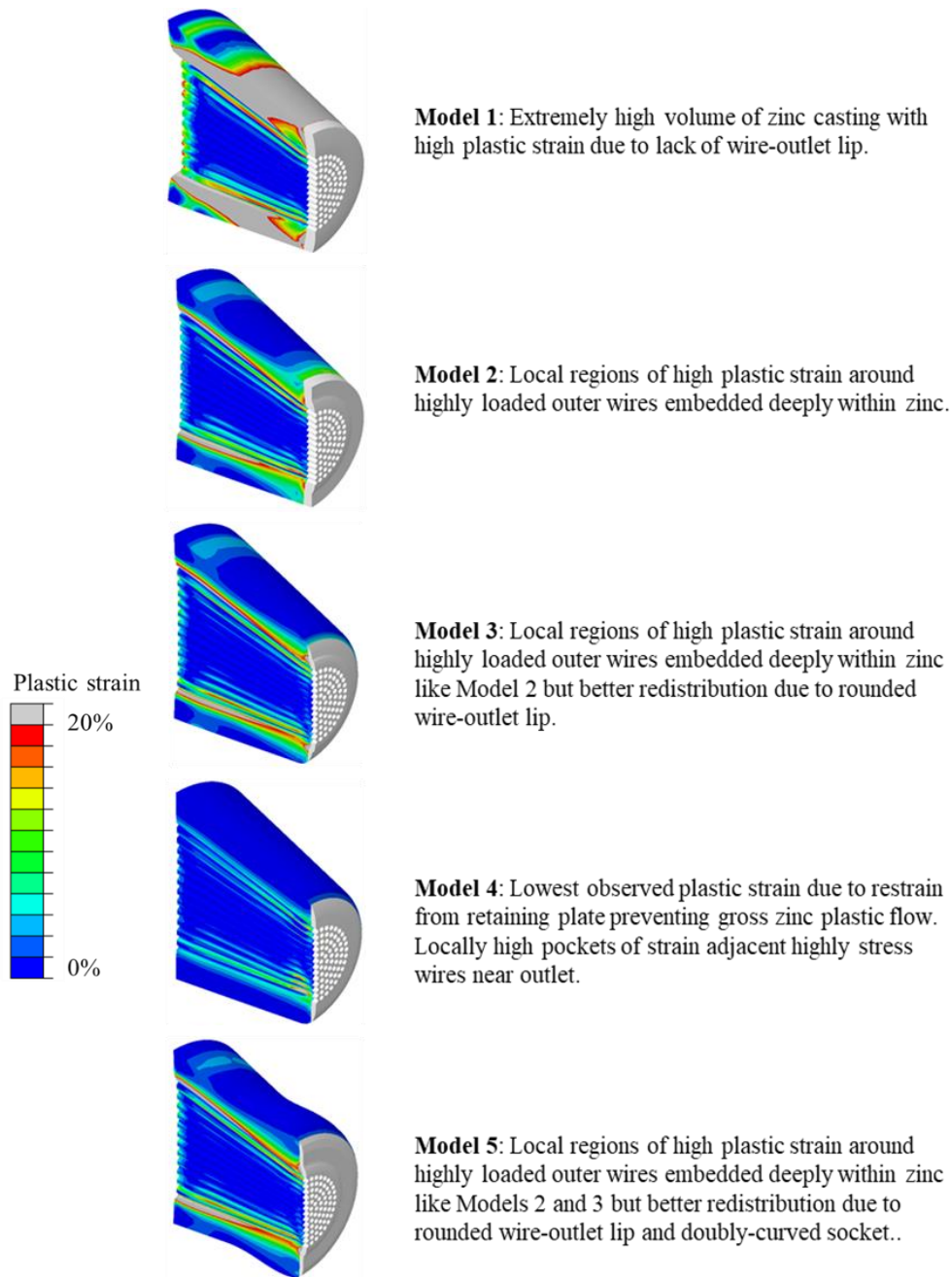


Figure 10. Variability in plastic strain within zinc casting shown for each design concept. Low plastic strain indicates lower propensity for creep mechanism to accelerate time-dependent creep failure.

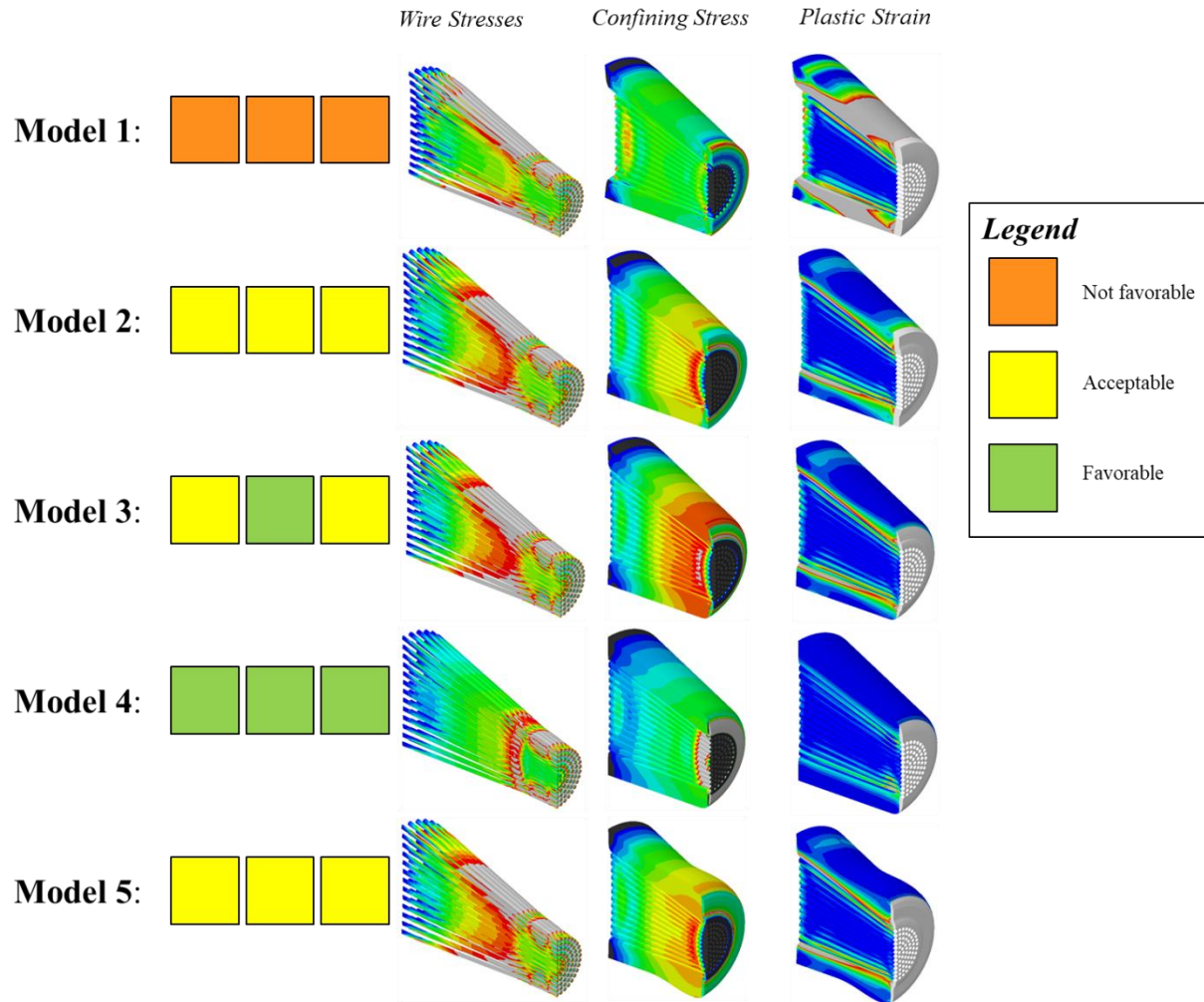


Figure 11. Qualitative ranking system of the five models considered in this study. Models 3 and 4 show most favorable stress and strain distributions for the socket parameters being studied.

4. CONCLUSIONS

Key findings from the Arecibo Aux M4N socket failure investigation guided the development of industry recommendations for revising civil engineering codes and design best practices. ASCE 19 versions were reviewed, and several recommendations were provided in the areas of in-service environments, design best practices, factors of safety, redundancy, creep, fatigue, proof test, inspections, and repair/replacement criteria. The following are specific industry recommendations directly related to the failure event:

1. Socket joint constituents should be verified to have positive structural margins for strength, fatigue, and creep failure modes for the service life of the socket for all design load combinations.
2. Proof test be implemented to screen for workmanship sensitive issues.
3. Periodic visual inspection of socket joints should include pass/fail criteria for zinc extrusion tied to a structural qualification test program that verifies the creep failure mode. Qualified processes such as cable replacement and socket joint refurbishment should then be defined to restore joint capacity in the event of failed inspection.

4. Civil engineering codes should be revisited to ensure that the design factors consider time-dependent creep effects in dead load dominated structures, those with high temperature environmental conditions, and when workmanship sensitivity to wire defects or brooming is known.

Design best practices included:

1. Design cable assemblies to fail in mid-span or adjacent to socket (not inside the socket).
2. Use a sufficiently high design factor of safety to preclude creep and fatigue failure mechanisms for these types of terminations
3. Qualification testing should include worst-case manufacturing imperfections that validate accept/reject defect criteria.
4. Develop defect acceptance criteria for post-fabrication screening, post-proof inspections, and in-service maintenance inspections.
5. Ensure the structural system has cable redundancy, and failure of a single cable does not result in catastrophic collapse of the whole structure.
6. If most of the total cable load is due to deadloads and the socket joint is designed to a factor of safety of 2.0, then the designer of spelter sockets should consider creep as a viable failure mode.
7. Keep positive structural margins for each of the cable assembly constituents.

Finally, design trade studies were conducted to increase the effects of zinc confinement, decrease the amount of shear stresses within the zinc that could lead to extrusion, and to shift the most critical failure mode so that it is outside of the socket joint. From all the design studies performed, the most favorable design was one with a retaining plate positioned within the socket to prevent gross zinc extrusion and concentrate the internal compression within the socket to shift the cable assembly failure mode to the cable outside the socket.

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