HIGH-STRENGTH STEEL IN THE LONG-SPAN RETRACTABLE ROOF OF RELIANT STADIUM

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SUMMARY

Signaling a new standard for stadiums throughout the world, Reliant Stadium - home of the Houston Texans and Houston Livestock Show and Rodeo - opened to rave reviews from players, fans and the media. Reliant Stadium is the National Football League's largest stadium, covering over 12 acres and comprising 1.9 million square feet. It is also the first NFL stadium with an operable roof, and at an area of 4 acres, it is the largest such roof in the United States. The translucent, fabric roof creates an instant architectural landmark and a positive new image for the city of Houston.

Design of the roof utilized a number of innovative concepts in both structural systems and structural materials. One of the keys to achieving efficiency in the long-span roof of Reliant Stadium was the use of high-strength steel in the form of ASTM A913 Grade 65. The benefits of high-strength steel may seem obvious at first, but Grade 65 steel must be applied with due attention to design and fabrication details for true economy. This paper presents a brief commentary on the rational use of Grade 65 in long-span structures, illustrated with the example of the Reliant Stadium retractable roof.

High-Strength Steel in the Long-Span Retractable Roof of Reliant Stadium

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INTRODUCTION

When Reliant Stadium opened in August of 2002 it not only replaced the Astrodome, the "eighth wonder of the world", but also set a new standard for sports facilities. The 1.9 million square foot stadium is home to the first retractable roof in the NFL, the league's closest luxury suites, largest scoreboards, and a unique palletized removable field system. Reliant Stadium also serves as home to the famous Houston Livestock Show and Rodeo. Its elegant high-tech architectural design seems to evoke the future with its silver paint, precast and metal panel cladding, walls of glass and a fabric roof that will literally glow for nighttime events.

The progressive spirit of the Reliant Stadium architecture is reflected in the engineering design and use of materials in the first-ever NFL retractable roof. As with all long-span roofs, the overall economy of the structural system is governed by both the structural form and the materials chosen for the individual roof elements. At the structural form level, the roof structure relies on an innovative composite steel-concrete truss system and a retractable roof clad with lightweight tensioned fabric. The element level economy of the roof structure is largely driven by the use of A913 Grade 65 steel. Use of such high-strength steel can present tremendous opportunities for pure weight savings, but to achieve true economy the weight savings must be complemented with proper attention to design and fabrication details. This paper presents a case study of the use of Grade 65 steel in the Reliant Stadium roof structure, along with general guidelines for the economical use of Grade 65 steel in long-span roofs.

Figure 1: Reliant Stadium (photo by Russell Andorka)

RELIANT STADIUM ROOF STRUCTURAL SYSTEM

Structural expression of the roof system in the architecture of Reliant Stadium was a key component of the overall aesthetic concept of the stadium. As such, the form of the roof had to seamlessly integrate with the interior sightlines as well as the exterior cladding while also accommodating a significant area of moving roof. To accomplish this, the roof structure is based around two large supertrusses that span along either sideline of the field (see Figure 2). These supertrusses serve as the support and track structure for the two bi-parting retractable roof panels. Each supertruss spans approximately 650 feet between concrete supercolumns located at the corners of the concrete seating bowl, and also cantilevers 167 feet past the supercolumns to accommodate the retractable roof panels in the open position. The bottom chord of the supertruss is gently arched to accommodate the sightlines of the seating bowl, creating a truss depth of 72 feet at the supercolumns and 50 feet at midspan.

The operable portion of the roof consists of two 350-foot span by 500-foot wide panels that ride along the supertrusses. Each panel contains five tapered depth trichord trusses. The roof surface of the panels is composed of a PTFE coated tensioned fabric membrane that spans between trichord trusses through anticlastic double curvature developed using a valley cable between each trichord truss. The roof is powered by forty 5 HP, 460 volt three phase electric motors, designed to open and close the roof in as little as ten minutes.

Two fixed trichord trusses spanning between supertrusses at each endzone support additional areas of fabric roof. A barrel shaped roof consisting of trusses spanning from the outside of the supertrusses to the back edge of the seating bowl provides full closure of the roof. A large box truss also spans between supercolumns at each endzone to support the massive stadium scoreboards. In total, there are more than 1.5 linear miles of primary long-span trusses in the roof of Reliant Stadium.

In response to the sightline driven form of the supertrusses, the structural behavior was controlled by making the supertrusses integral with the supporting concrete supercolumns. This created a large portal frame, shifting maximum moments away from the midspan, where the truss depth is minimum, to the supercolumn area, where the truss depth is maximum. In addition, the concrete slab at the top of the supertruss that was required for a service platform for the retractable roof was utilized structurally by making the supertruss composite with the slab. The concrete slab serves as a part of the top compression chord of the truss through shear connectors placed along the steel top chords. The composite steel/concrete supertrusses on Reliant Stadium are believed to be the largest ever used in a building structure.

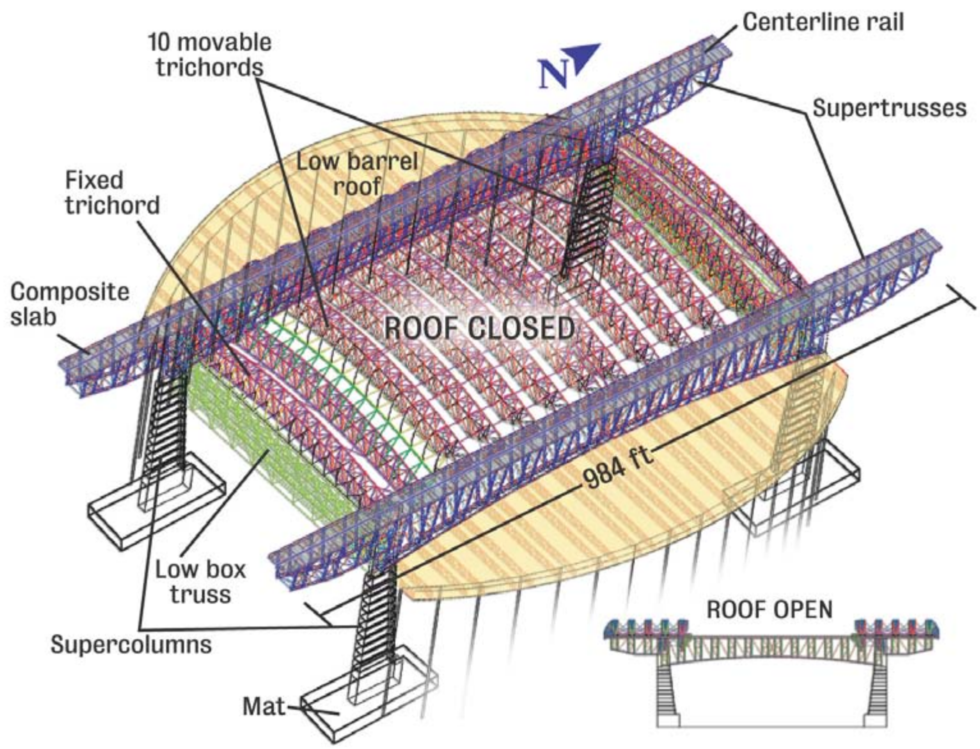

Figure 2: Reliant Stadium Structural System

ROOF TRUSS MEMBER SHAPING AND DESIGN CONSIDERATIONS

The forms of the various long-span roof trusses used in Reliant Stadium are shown in Figure 3. For the highly loaded supertrusses, compression members were made of double-W14 sections laced together with single angles. This approach was taken in order to keep individual member unbraced lengths low to fully realize the benefits of using Grade 65 steel. Diagonals were almost always in tension and could be made of single W14 shapes. A typical bay of the supertruss during erection is shown in Figure 4. For the shorter span trichord trusses and endzone box trusses, single W14 chord members were used. In these trusses efficient bracing configurations kept compression unbraced lengths low, making the use of laced compression members unnecessary. Secondary bracing members for all trusses were typically double angles.

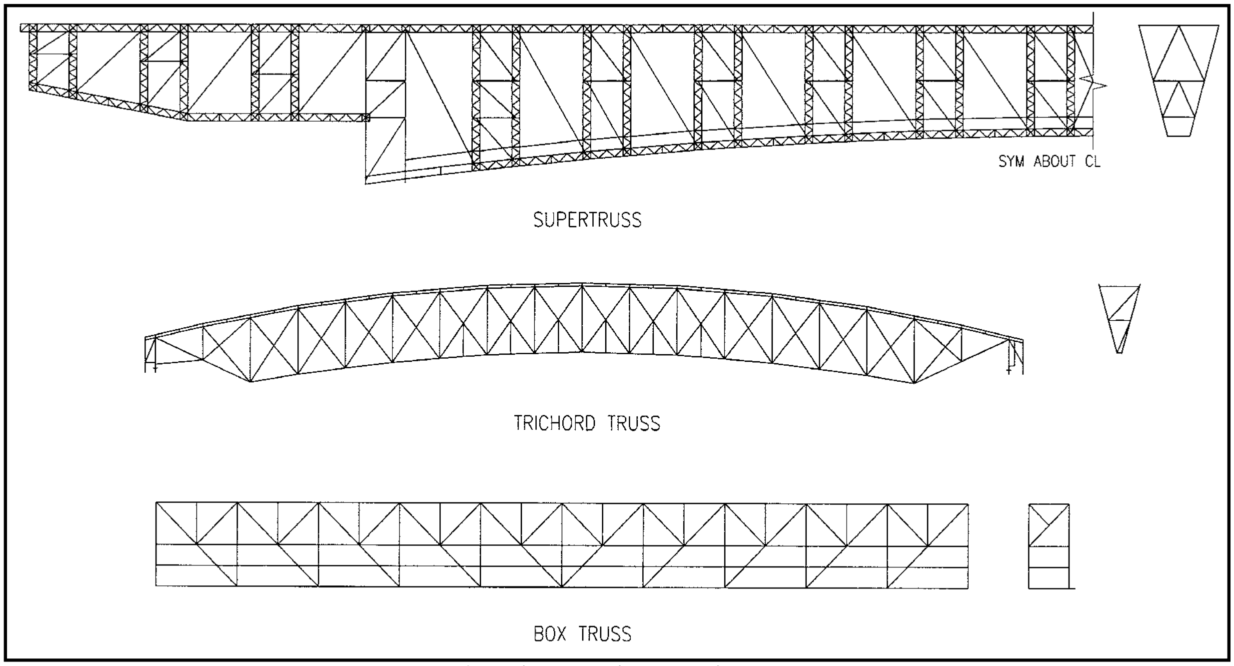

Figure 3: Reliant Stadium Roof Truss Forms

Figure 4: Typical Bay of Supertruss

The truss elevations shown in Figure 3 illustrate several important points about efficiently using Grade 65 steel. Extra attention must be given to keeping unbraced lengths of compression members down to realize the full benefit of the higher strength. For tension members, strength will often be governed by the fracture capacity of the section. The full benefit of Grade 65 steel can often be captured by providing lead-in bolts and member end supplement plates to develop the full yield capacity of the section. In this case a balance must be established between the weight savings in the member versus the fabrication costs of supplemental plates. This effect is quantified further below. Tension members with long lengths and end supplemental plates are usually the most economical application of Grade 65 steel.

It is important to note that only certain rolled shapes and sizes are available in Grade 65. The availability is usually only for larger sizes, leading to the general rule that Grade 65 should only be specified for large, heavily loaded structures. A general guideline to availability is given in Table 3. Before specifying Grade 65 steel, a structure should be evaluated for the general stress levels and ranges of sizes required for members. If larger shapes (for trusses, typically meaning W14X90 and bigger) are required for only a small percentage of the total tonnage, it is probably not economical to specify Grade 65. However, if most members are of these larger shapes, Grade 65 can provide significant opportunities for cost savings. For example, in Reliant Stadium the trusses that form the side barrel roofs were of shorter span and required only a few large W14 chord shapes. Since the mill order for the barrel roof trusses was sequenced separately from that of the main roof, A992 Grade 50 steel was specified. Consideration should also be given to maximum available lengths to avoid unnecessary expensive splices (see "Availability" below).

CONSIDERATIONS FOR DESIGN OF COMPRESSION MEMBERS WITH GRADE 65

As with all compression members, truss chords in Grade 65 steel rely on maintaining short unbraced lengths for economy. To further understand the economy of Grade 65 steel relative to Grade 50 steel in compression members, consider the column curve shown in Figure 5. For very short unbraced lengths, the full weight savings of 30% can be realized. For most real structures it is impractical to design in this range. At longer unbraced lengths the benefit of the higher strength is of course lost as the column enters the Euler buckling region. The practical breakpoint is at a KL/r of around 100, where the weight savings of about 5% offsets the currently 3-5% higher cost of Grade 65 steel. However, most well proportioned trusses will have bracing that allows far greater weight savings. As shown in Figure 5, the Grade 65 compression members used in Reliant Stadium typically had controlling KL/r ratios between 35 and 60. The average weight savings in this range was around 25%.

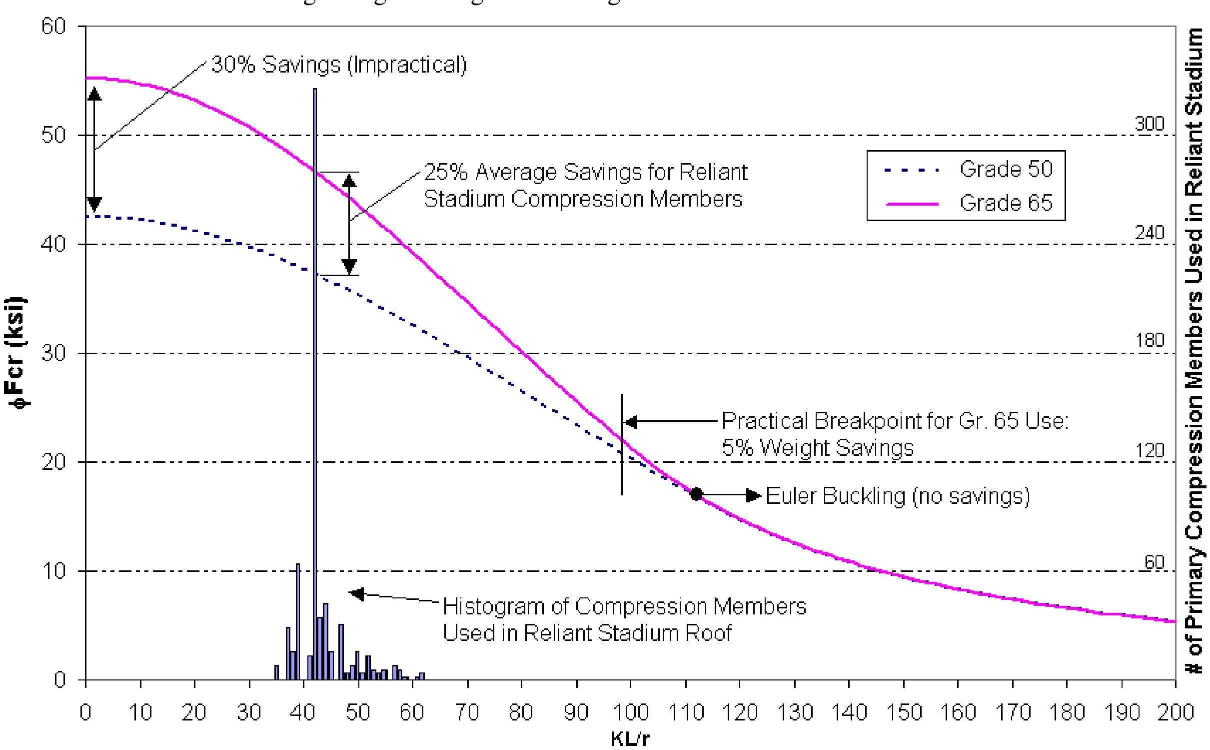

Figure 5: Grade 50 vs. Grade 65 Column Curve

Several strategies may be employed in large trusses to condition unbraced lengths to be in the economical range of Grade 65 usage. The primary strategy on Reliant Stadium was the use of built-up laced compression members in the supertrusses. In addition, several types of stability bracing were employed. Laced truss posts were braced torsionally through W14 cross-bracing working in flexure. Similarly, torsional bracing of the bottom chord built-up members was provided through flexural members in the catwalk structure located in the bottom chord. Design of truss compression members also considered built-up member buckling including shear effects, torsional buckling of individual members, and overall buckling of the trusses.

CONSIDERATIONS FOR DESIGN OF TENSION MEMBERS WITH GRADE 65

At first glance, it would seem that Grade 65 steel should provide a direct 30% weight savings over Grade 50 for tension members. However, most truss tension members have bolted end connections and are controlled by fracture on the effective net area. The Fu/Fy ratio (based on min. specified values) of Grade 65 steel is 1.23 versus 1.3 for Grade 50 and 1.61 for Grade 36, making fracture a critical consideration for sections proportioned on the basis of yielding on the gross area (note that, in contrast, seismic applications must limit the Fu/Fy ratio for ductility concerns). The strategies used on Reliant Stadium to efficiently design Grade 65 tension members include use of lead-in bolts and supplemental plates in connections. Different strategies should be employed for welded connections, where fracture is likely not a major concern for reasonable length connections.

Supplemental plates, as shown in Figure 6, are often provided at the ends of tension members to increase the net area in compensation for bolt holes. At present, plate material is not economically justifiable in strengths greater than 50 ksi, and therefore supplemental plates are typically specified as Grade 50. It is of interest to note that the full A_eF_u of the differing grades (Gr. 50 plate; Gr. 65 wide-flange) may be added in the net section check due to the large strains that must develop prior to fracture. Strain compatibility enforced by the welds will ensure that the lower strength supplemental plate may not fracture until the higher strength Grade 65 member reaches the critical fracture strain. Note that this concept also applies to the use of A36 plate as Grade 65 supplemental plate. The slight difference in fracture strain between A913 and A992 or A36 (see Table 1) may generally be ignored.

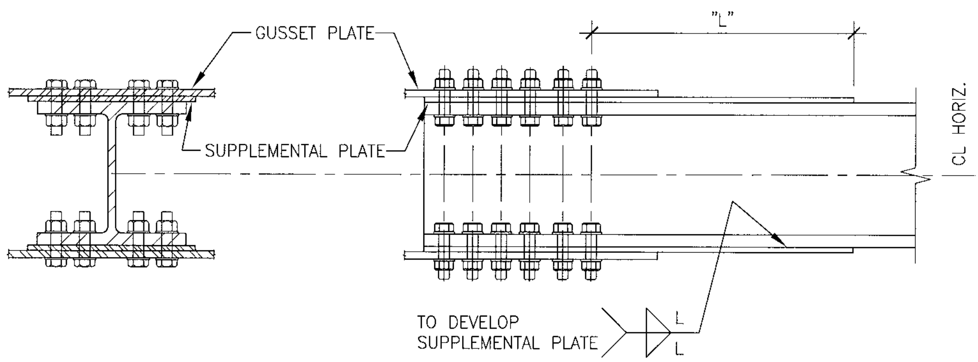

Figure 6: Typical Supplemental Plate Detail

Economic application of supplemental plates depends on member length. The designer is presented with the option of either upsizing the member to satisfy the fracture check, or providing supplemental plates at the member ends. The fabrication costs of the supplemental plates must be compared to the weight premium for upsizing over the entire member length. Fabrication costs associated with handling, drilling, painting, and welding may make the fabricated cost of supplemental plates as much as twice the material cost of the member on a per ton basis. Figure 7 presents a rough guide to the economic break point in member length between upsizing and providing supplemental plates. In general, supplemental plates are best used for long members, while upsizing the member for the net section is the best practice for short members. If supplemental plates are to be used, the premium will be slightly higher for Grade 65 than Grade 50 rolled shapes due to the Fu/Fy ratios mentioned above. If supplemental plates are not to be used, as for shorter members, it is advantageous to use Grade 65 steel.

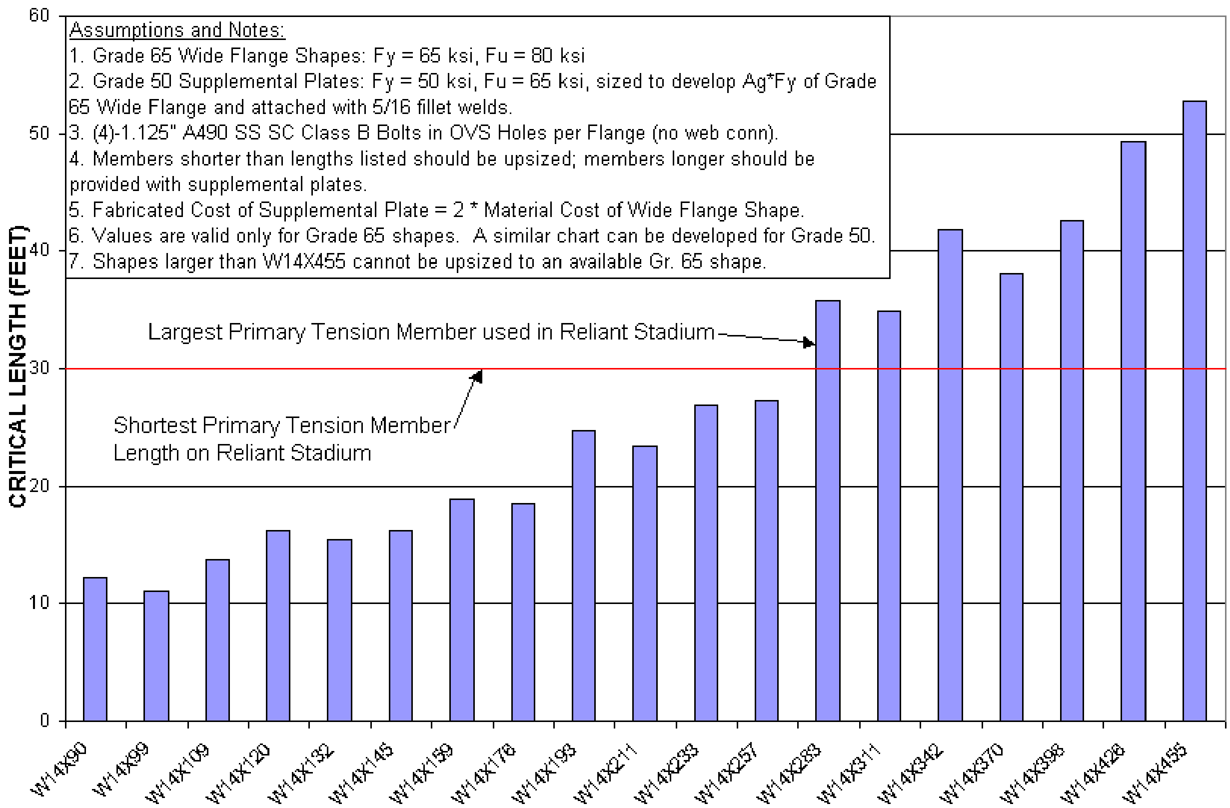

Figure 7: Minimum Lengths for Economical Use of Supplemental Plates for Grade 65 Tension Members

RELIANT STADIUM RETRACTABLE ROOF SAVINGS FROM GRADE 65

The percent of Grade 65 steel used in the various roof elements in Reliant Stadium varied based upon the level of loading and span for each element. In the heavily loaded supertrusses and box trusses, Grade 65 steel constituted about one-third of the total tonnage (including connections). Since they were clad in light-weight fabric and supported only direct roof load, only about 15% of the total weight of the trichords was of Grade 65 steel. In total, roughly 3300 tons of A913 Grade 65 steel was used in Reliant Stadium, constituting 26% of the overall tonnage. Use of Grade 65 steel led to an estimated overall tonnage savings of 825 tons, about 7% of the total roof tonnage (significant savings for a project of this size). For the members that used Grade 65, the average weight savings for the member was between 20 and 25%.

The full economic benefit of using Grade 65 is difficult to quantify, but fabrication, handling, and erection savings due to reduced weight did magnify the pure material tonnage savings. In addition, the lighter steel weight led to savings in the supercolumns and foundations. The light steel weight was crucial in fitting the supertruss baseplates in the very limited bearing area available on top of the supercolumns. The lighter steel weight made possible by using Grade 65 steel also helped to control differential settlement between the supercolumns and the bowl concourses.

CONSIDERATIONS FOR FABRICATION AND ERECTION OF GRADE 65 SHAPE MEMBERS

A913 Grade 65 is fully pre-qualified in the Structural Welding Code AWS D1.1 since 1996, thus weld procedure qualification tests are not necessary. Moreover AWS D1.1 allows welding of A913 Grade 65 without preheating, for temperatures above 32 degrees and provided low hydrogen (H-8) electrodes are used. If low hydrogen electrodes are not used, the Welding Code requires A913 Grade 65 preheating temperatures similar to regular Grade 50. Also, when welding Grade 65 to Grade 50, the latter requires preheating. The very low chemistry and thus low maximum allowable Carbon Equivalent value (0.43%) of A913 Grade 65 shapes is the reason for the advantageously reduced preheating requirements. Besides reduced preheats, A913 was welded in the shop and a few isolated cases in the field using the same procedures as for Grade 50, with the exception that for the few connections with complete joint penetration shop welds in tension, an E80-type filler (matching Grade 65 properties) had to be used, as required by AWS D1.1. All other welded joints, which were either full penetration welds in compression, partial penetration welds, fillet welds, and welds to Grade 50 were carried out with the same filler material used for Grade 50. The E80-type electrode was the self-shielded flux-cored wire NR-311-Ni (meeting properties of E80). The E70-type electrode was a gas-shielded flux-cored wire E70-T9. It should also be pointed out that the extra cost for NR-311-Ni (some 10%) was more than compensated by the easier slag removal – which the welders greatly appreciated.

Sawing, punching, drilling and flame cutting of structural shapes in Grade 65 was performed using the same procedures as for Grade 50 material. No change in saw blades and drill bits was necessary – but depending on their quality, they may wear more.

In terms of erection, the member weight savings resulted in direct savings in trucking and more importantly in savings to rent cranes for lifting the truss segments. Indeed, commonly available crane equipment sufficed, whereas Grade 50 would have required expensive special cranes – a cost difference of 250,000 USD.

ASTM A913 GRADE 65: PRODUCTION, SPECIFICATION, PROPERTIES, AVAILABILITY

While the mechanical properties of common structural steels, like A992, A572 or A36 rely on the chemistry of the steel, the mechanical properties of A913 steels result from its chemistry plus an advanced thermo-mechanical treatment at rolling – called Quenching and Self-Tempering. QST is an in-line process, in which immediately after rolling, the shape is rapidly cooled with water and reheats itself by a temperature equalization through a heat-flow from the inside to the outside of the material. QST allows a combination of three formerly incompatible properties:

- Very high yield and tensile strength
- Excellent Charpy V-Notch toughness, even at low temperatures
- Outstanding weldability

and this up to very large flange thicknesses of 5 inches, like W14x730.

The optimal combination of strength and toughness results from the very fine grain size originating from the QST process. The outstanding weldability of the A913 steels, allowing in most conditions welding without preheating, is due to the very low amounts of alloying elements – and accordingly low Carbon Equivalent (CE) values. CE = Mn/6+(Cr+Mo+V)/5+(Cu+Ni)/15.

ASTM A913 / A913M – 01 is the current Standard Specification for Grade 65, but includes also Grade 50, 60 and 70. A913, which first appeared in 1993, covers structural steel shapes processed by the Quenching and Self-Tempering (QST) process. Table 1 compares the required tensile properties of A992 and A913 Grade 65:

Table 1: Comparison of A913 Grade 65 and A992 (Grade 50)

Grade	Yield point Ksi [Mpa]	Tensile strength min. ksi [MPa]	Minimum Elongation 8 in. [200 mm] %	Minimum Elongation 2 in. [50 mm] %
A992 [345]	50-65 [345-450]	65 [450]	18	21
A913-65 [450]	min. 65 [450]	80 [550]	15	17

In terms of Carbon Equivalent, A913 has a maximum allowable value of 0.43% for Grade 65 and 0.39% for Grade 50, whereas A992 has a maximum allowable value of 0.45%, increased to 0.47% for Group 4 and 5 shapes – which are jumbo shapes. Table 2 compares the required chemistry of A992 and A913 Grade 65.

The available shape sizes in A913 Grade 65 are presented in Table 3. The theoretical maximum mill length is 104' for most sizes. The usual practical shippable length is 80' maximum. Lengths greater than 80' need inquiry. The following 5 sizes have currently a maximum length lower than 80': W14x550 (70'-6''), W14x605 (63'-3''), W14x665 (56'-5'') and W14x730 (50'-10'').

Table 2: Chemical Comparison of A913 Grade 65 and A992 (Grade 50)

Element	Maximum Content in %	
	A992 [345]	A913-65 [450]
Carbon	0.23	0.16
Manganese	1.50	1.60
Phosphorus	0.035	0.030
Sulfur	0.045	0.030
Silicon	0.40	0.40
Copper	0.60	0.35
Nickel	0.45	0.25
Chromium	0.35	0.25
Molybdenum	0.15	0.07
Columbium	0.05	0.05
Vanadium	0.11	0.06

Table 3: Availability of A913 Grade 65 Shapes

Readily available	Available (check first)
W14 x 90 thru 730	W12 x 65 thru 230
W36 x 150 thru 439	W24 x 84 thru 370
W40 x 167 thru 503	W27 x 102 thru 129
W44 x 230 thru 335	W30 x 108 thru 148
	W33 x 130 thru 169

CONCLUSIONS

The Astrodome set the standard for its time and so too will Reliant Stadium. Its unique retractable roof and the incomparable fan amenities promise not only to bring NFL football back to Houston in grand style, but also to create a new home for the largest rodeo event in the world – all in an open air or fully enclosed air conditioned environment. The successful completion of the stadium in a hyper fast-track schedule of 30 months was made possible only through extensive collaboration and cooperation between all design and construction team members.

A913 Grade 65 steel played an integral role in the success of the Reliant Stadium roof, and will continue to be an important tool for economical realization of future roofs. Practical economical integration of Grade 65 into long-span roof structures requires careful attention to both design and fabrication details, but when properly applied Grade 65 can present significant opportunities for savings. Future developments in materials technology will hopefully lead to greater opportunities for designers to create new progressive and economical structural systems.