The ESG Report

FALL 2009

DESIGN FACTOR STRESS:

HEADACHES CAUSED BY COMPOUNDING DESIGN REQUIREMENTS

A professor in structural design once said to his class, *"I do not care what your parents named you. When you come into my class your first, middle and last name will be 'bending, shear, and deflection'. This will remind you that you will always check at least these three things."*

Even now that memory is comical, but it is also a poignant reminder of basic engineering concepts that are (almost) always checked. We'll come back to them in a moment…

When clients ask us to perform an engineering review on an entertainment system, most often it is because of a specification requirement. Very few building codes require engineering analysis for things like pipe battens and rigging systems, but project specifications for entertainment venues frequently do include such a requirement. How do engineers approach this? In the absence of any performance specification, the engineer verifies actual loads and then compares them with allowable loads permitted by code. The AISC Steel Construction Manual provides direction for analyzing steel members in a myriad of conditions.

Allowable loads are determined by applying a factor of safety (or design factor, used interchangeably here) to a material's yield strength. Most of you recognize the application of a design factor as a cushion of sorts so that the material isn't working too close to its failure, or yield point. However, that's an oversimplification of the many things that come into play. What happens if an engineer's seal is required by specification, but not by applicable code?

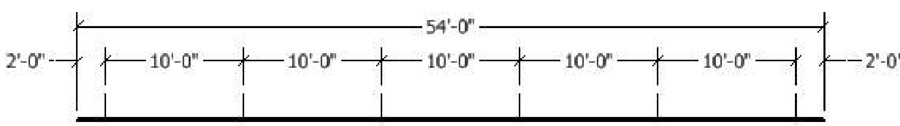

Figure 1

The engineer begins by establishing the basic design criteria; these can be as required by code or other applicable design standard, defined by a project specification, or the engineer can make assumptions using commonly accepted practice. These assumptions must be made in order to verify which condition controls the analysis. Interaction of the design assumptions affect the actual and allowable stresses calculated for a structural member. At least, these stresses occur in bending, shear or deflection – which brings us back to our three basic engineering monikers.

Now more than ever, our industry is faced with specifications containing requirements that can unintentionally interact, often creating onerous engineering design criteria. Meeting these requirements to the letter often results in higher project costs – and a big stress headache for the manufacturer, installer, designer and ultimately the owner.

In this edition of the ESG Report we will use simple examples to explain some of those design criteria, and to show how combinations of commonly seen performance specification criteria can interact unfavorably to result in significantly over-designed systems.

Let's start with something simple: a pipe batten. Our example batten will be 1½" (nominal diameter) ASTM A53 Schedule 40 pipe, 54' long, supported on (6) lift lines, each spaced 10' apart, as illustrated in Figure 1.

About the Author

Richard Nix is the Division Project Coordinator. His range of expertise includes rigging system design and installation, as well as several years as a stagehand and staff rigging supervisor. He is the author of many technical articles and has participated in ESTA's standards development efforts for over twelve years.

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There are no code requirements for a pipe batten per se. However, the AISC Manual of Steel Design contains methods for defining the allowable stresses in structural steel beams and every US building code refers to these design methods. In addition, the entertainment industry has another viable reference: ANSI E1.4-2009, *Manual Counterweight Rigging Systems* contains performance criteria guidelines for rigging system components, including battens. The engineer is permitted to use such published standards as a basis for design, as long as the minimum requirements in the AISC manual and applicable building codes are met.

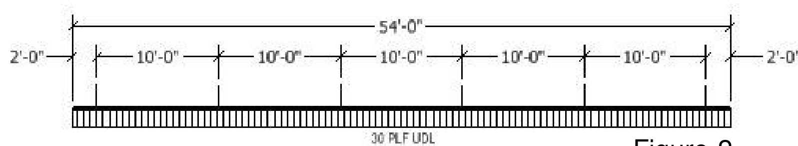

Figure 2

E1.4 contains the following performance requirements for pipe battens:

- Battens must accommodate 30 lbs per liner foot (PLF) minimum design load, uniformly distributed along the length of the batten (*Uniform Distributed Load* or *UDL*);
- The deflection caused by a 100-lb point load located at midspan between suspensions can be no greater than the ratio L (length of the span = distance between supports) divided by 180, or L/180 in E1.4 nomenclature.

Translated, our example batten's total uniformly distributed design load is 1,620 lbs, and the deflection caused by the defined 100-lb point load cannot exceed 120"/180 or just a little over 5/8". Using E1.4 as a guideline makes things easier because it clearly defines design criteria, but how can we determine design loads without this kind of guidance?

No matter what, the load must still be defined. One way to determine the maximum batten load in a counterweight rigging system is by arbor capacity. For example, if an arbor can accommodate up to 6' of standard 4"-wide counterweight (about 15 lbs per inch of weight) that's 1,080 lbs. Let's assume an arbor self-weight of 120 lbs, for a total of 1,200 lbs. Thus, the batten design load would be 1,200 lbs/54' = 22.2 (say 23) PLF.

By comparison, we could use either design load basis: 30 PLF because E1.4 is a recognized standard or 23 PLF because the arbor physically cannot hold more weight under proper use conditions. I should mention that E1.4 does not provide a minimum design factor for arbors or battens. Rather, it requires a qualified person (i.e. an engineer) to determine appropriate design factors for all components not in the tension load path. What's acceptable in this case? Well, that's an interesting question. From an engineering perspective, the very structure to which a rigging system is attached was likely designed using a 1.67 factor of safety. However, design factors in the entertainment industry range from 4:1 up to 8:1 or even 10:1 – but we still need to think about whether these factors are applied relative to yield, relative to breaking strength, or even relative to a manufacturer's published working load limit (WLL). Our topic though, is not design factors specifically; it's about how combinations of performance design criteria can interact with each other unfavorably. Let's get back to our example, which is illustrated in Figure 2 with a 30 PLF load across the entire batten length.

A typical pipe batten is ASTM A53 Grade B material, with a Yield Strength (F_y) = 35 Ksi. Using commonly accepted design factors for steel, the allowable stress is about 21 Ksi. But, if a 5:1 design factor versus yield is required, the allowable stress drops to 7 Ksi.

Figure 2 (above) illustrates a 30 PLF load across the entire batten length.

Using computer analysis, we determined that the maximum stress in our example batten is about 11 Ksi. Figure 3 (below) shows the results in a graphically exaggerated example of the deflection, along with the associated bending stresses (the table shows the maximum stresses present in this example, even though the resolution is too small to see the actual areas of stress concentration). The maximum deflection occurs at each offstage lift line connection and is about .34" – just a little more than ½ the allowable deflection.

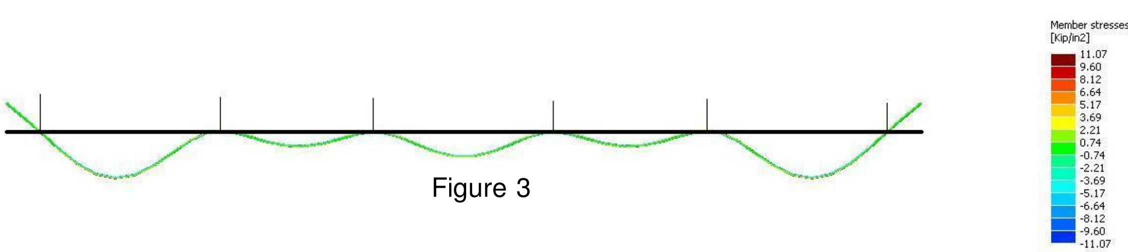

Figure 3

Figure 4 (above) shows a 100-lb point load applied per E1.4 requirements, and Figure 5 (below) illustrates the corresponding analysis result. The maximum bending stress is only about 5.3 Ksi with a calculated deflection of about .23".

These two checks show that our example passes analysis for both deflection and allowable stress, using commonly accepted practice along with E1.4 design criteria. Now

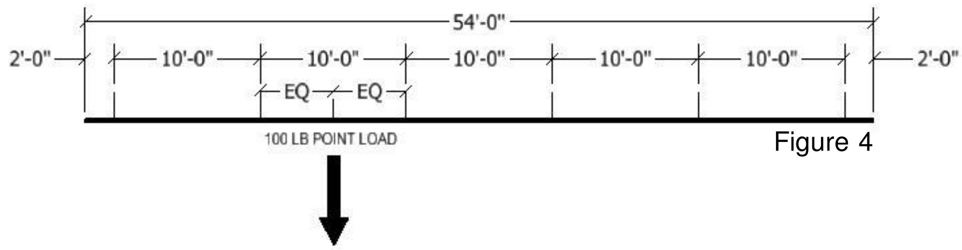

Figure 4

let's see what happens when a 5:1 design factor is required. As shown earlier, applying this design factor results in an allowable stress of 7 Ksi. As such, the batten will fail analysis for the UDL check because the calculated maximum stresses shown in Figure 3 already exceed those allowable when applying the larger design factor. How can we resolve this? Intuitively, we might simply increase strength and stiffness by using a Sch 80 pipe instead of Sch 40. This reduces the calculated maximum deflection to about .27" but (as shown in Figure 6 below) even a Sch 80 pipe doesn't quite make it because at about 8.5 Ksi, the calculated stresses still exceed the 7 Ksi permitted when using a 5:1 design factor.

As alluded to before, one important consideration is that pipe battens are not always uniformly loaded, nor are they always loaded with single point loads. Should we consider those operational conditions? Certainly, but they are not necessarily required to be considered by a specification, whereas the worst anticipated load combination must always be considered under applicable code requirements. Alternatively, load cases might also be limited by the application of operational restrictions, which describe or limit the general acceptable loading conditions for proper use. For example, E1.4 does not explicitly account for a batten supporting a drapery track, where the drape could represent either a uniformly distributed load (the track, with curtain closed), or a combined load of the track (UDL) with an open drape (concentrated loads at each end of the track).

Here at ESG we always check both conditions. Practically speaking, and unless the drape is unusually large, meeting E1.4 design criteria will satisfy both of these use conditions. That may not necessarily be the case if alternative design factors or deflection criteria work against each other.

Those of you who understand this discussion can relate it to something a little more complex by considering how an inordinately high universal design factor can effect conditions such as bending stresses in a block's base angles, or localized buckling in a block side plate – and how different the allowable stresses might be if the block is upright versus underhung.

Remember, this is a highly simplified discussion intended to illustrate how – even with the best of intent – design criteria can interact unfavorably. Think about it: Is a double-pipe Vierendeel truss batten really necessary when a single Sch 40 pipe batten is strong enough under a reasonable load condition?

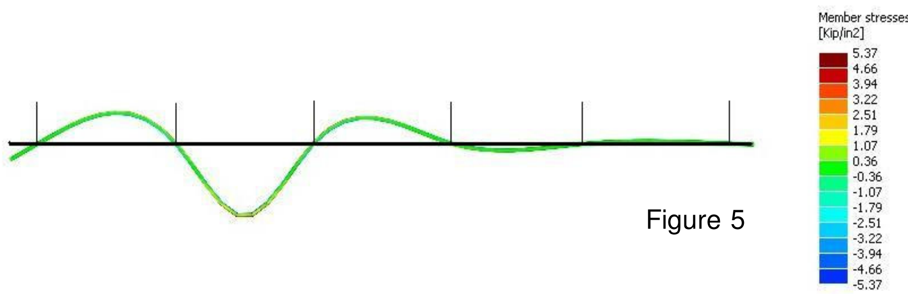

Figure 5

Our engineers (all of whom, at some point during the writing of this article, were aptly named *Bending, Shear, Deflection)*, have a thing or two to say about it. They spend some of their engineering time figuring out solutions to relieve your design factor stress. So, when specifications cause you a stress headache, take two aspirin and call us in the morning.

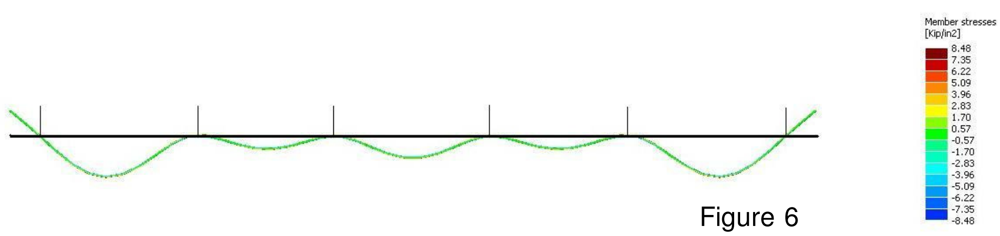

Figure 6

Disclaimer: This article is not intended to be a thorough treatment of the topic of structural evaluation. Local, state and national building codes should be consulted. The author cannot be responsible for any evaluation based solely upon this article.

A DIFFERENT SORT OF WRAP-UP?

Over the past few years, some of our readers have asked questions about how to wrap slings (specifically, polyester roundslings) around aluminum truss chords. Just for fun, and for those of you who use truss regularly, we thought we'd wrap up this month's ESG Report by posing the question back to you: What are your best practices for accomplishing a roundsling connection to a truss span? Consider this a straw poll of sorts to hear not only what you think, but also what truss manufacturers recommend.

Maybe there are multiple ways to do this. If so, what are the factors that might motivate you to choose one method over another? Figure 1 shows the side view of a very generic truss diagonal layout. The truss you are most familiar with might also have additional vertical brace members intersecting the panel points – that's okay.

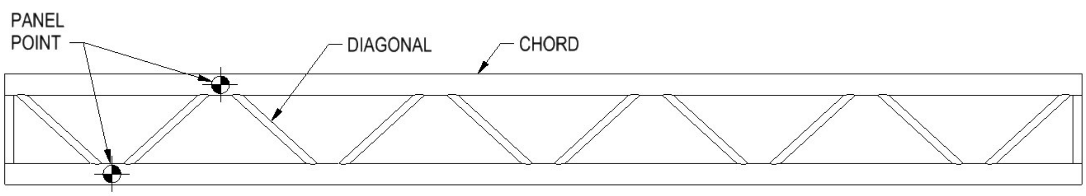

Figure 1

One recommendation we're aware of is to choke the bottom chord and wrap the top chord, as shown in Figure 2. However, shouldn't those wraps only be made at the truss panel points? If so, have you ever wondered how you can accomplish this by wrapping both the top and the bottom chord? The diagonals only form panel points at either the top chord or the bottom chord, so in this case one wrap will always be located where it is inconsistent with the recommendation. Alternatively, you could choke either the bottom chords or the top chords only. Would it matter? Why?

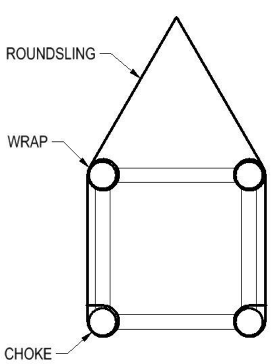

Figure 2

Consider two examples. The basic criteria for both examples is a simple span of truss supported on two points, each equidistant from the end of the span. The truss in one example is a box-profile truss, while the other truss is a triangular profile. Would you wrap the sling(s) differently in either example? In example 2, should you hang the truss point down, or point up?

These aren't trick questions, and you may be surprised at how many different correct answers there are. So don't be afraid to send us your feedback. We'll respond in kind by dedicating an entire discussion to the questions – and the answers – in an upcoming issue of the ESG Report.

Send your feedback or suggestions care of Richard.Nix@EntertainmentStructures.com. We're listening!

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