GUSSET PLATE TRIAGE FOR STEEL TRUSSES IN WASHINGTON STATE

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BIOGRAPHY

Patrick Gallagher graduated from Washington State University in 1999 having earned a Bachelor of Science Degree in Civil Engineering. Following graduation, Pat worked the next four years at several engineering firms and in various engineering capacities prior to coming to work for Washington State in 2004. Pat is currently employed as a Bridge Engineer in the Bridge and Structures Design Office, for the Washington State Department of Transportation (WSDOT).

Pat's experience in bridge design covers steel and pre-stressed concrete girder bridges, bridges in high seismic regions, retro-fit structures including repairs, bridge inspections and Pat is a steel sign bridge specialist.

Pat has spoken at a number of Bridge Engineering Conferences, including the 2012 NSBA World Steel Bridge Symposium in Dallas, Texas.

In his personal life, he's been married 13 years, a father of four, moonlights his engineering services, and is a member of the Centralia City Council.

Known for his enthusiasm and his thinking "outside the box" attitude, Pat routinely champions aspects of bridge design that interests him most. These include: Fracture Critical Steel Structures, Steel Trusses, and Accelerated Bridge Construction.

SUMMARY

Gusset rating is routinely performed in response to the collapse of the I-35W Bridge in Minneapolis, Minnesota on August 1, 2007. This presentation describes WSDOT's reaction to the task of rating gusset plates on its inventory of bridges and describes a new tool developed by WSDOT and the University of Washington to rapidly evaluate the rating capacity of gusset plates.

This paper will describe the magnitude of the gusset rating task and some specifics in developing the Gusset triage. It will also lightly touch on an example of a more notable bridge in Washington and describe where WSDOT is headed with gusset plate load rating.

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Introduction

In the wake of the collapse of the I-35W Bridge in Minneapolis, Minnesota in 2007, states have been tasked with evaluating gusset plates. This structure was modified a number of times within its service life, and construction materials stockpiled on the bridge deck led to the collapse, killing 13 people. It's the understanding of the engineering community that an inadequate gusset design was constructed on that bridge, and on August 1st, 2007 the bridge finally saw its ultimate load, dropping the span in the Mississippi River (5). This report describes some of the analysis considerations Washington State has given to the task of evaluating gussets and describes a simplified and reasonably conservative method for rapid evaluation of steel bridge gussets developed by the Washington State Department of Transportation (WSDOT).

In this report, a brief explanation of the triage method is given, and example is provided to demonstrate the value of the triage method. For a complete understanding of how to perform a triage analysis, and a more complete defense of the method, the reader ought to review the research that went into developing the Triage Method (1). Since the publication of the cited research, more research has been done, more failure modes have been identified, and more checks may be applicable. This paper addresses what WSDOT did in the early stages of gusset evaluation development.

Motivation for a New Method

There are two main motivations for determining a simplified method for evaluating gussets, and both of them have to do with the cost of engineering time.

The first reason is to rapidly meet the requirements of the Federal Highway Administration's (FHWA) requirement gusset plates be evaluated, regardless of condition or historically low concern. Load rating has historically been a bit of a reactionary process where main structural elements are evaluated and lesser portions are assumed to be adequate, except where the load rating engineer deems necessary for a special evaluation. Gusset plates have traditionally been lumped into this "not a problem" category and rarely evaluated when a bridge is load rated. So as a result of a new requirement to evaluate gusset plates, every gusset plate on every truss on WSDOT's inventory needed to be evaluated and rather quickly.

Realize that failure of the bridge in Minnesota was a very rare case of a design error being brought to light. It's reasonable to assume almost every bridge was properly designed to the criteria of its day, and the likelihood a gusset plate being severely inadequate is pretty low. Many of them are below modern design standards. But few are likely to result in something as dramatic as the I-35 W collapse. What's being sought after with the analysis of gusset plates is well compared to finding a needle in a haystack. And the assumption of "almost every bridge being adequate enough" is being tested, seeking out those rare few that might bring a span down soon.

The second reason is for the convenience of rapid repair. The recent collapse of the Skagit River Bridge on Interstate 5 in Washington State brought to light corrosion in many of the joints in the portions of the bridge that did not collapse. Debris was allowing moisture to sit and soak the rivet heads in many bottom chord joints, rusting those heads and reducing the strength of those connections. While this corrosion was not likely a significant contributing factor to the collapse of Skagit River Bridge, having a triage evaluation performed on the bridge previously made quick work of determining how many rivets could be replaced at one time in order to restore the connection capacity affected by deteriorated rivets.

Looking back upon the last seven years, and now discussing a triage method, one might wonder, why "triage" now? Why not implement a triage method in 2007? Being gussets were a new item to rate to such a degree in 2007, WSDOT determined that the engineering costs were less to develop a new method and implement that, than to simply implement the FHWA Method universally among all steel truss bridges. And realize the term "triage" is a bit misunderstood.

The term "Triage" was assigned to this method as a means to describe the simplicity of the method, not necessarily it's timing to the I-35 Collapse. And while FHWA has given states a window of time to evaluate their gusset plates' sufficiency, the term "triage" might apply to the immediacy of this time frame in the global evolution of bridges, not the recent few years. In a time span of centuries where truss bridges have been commonplace, a few years might be considered "quick." Furthermore, in the year 2014, we're looking back on much of the work WSDOT performed. As one considers the timing of WSDOT's prior work, the term "triage" becomes more appropriate as it was performed closer to August 2007. Regardless of the philosophy, the term "triage" has been given to this method as a way to simply identify it and tie it to recent and relevant events in bridge history.

Washington State Steel Bridges

WSDOT's truss inventory includes over 130 steel truss bridges ranging from the common simple span truss supporting a two lane highway, to very complex and intricately detailed trusses supporting up to 12 lanes and constructed with a wide array of erection stresses built in. Put WSDOT's truss bridges end to end at you'd have a truss structure almost 28 miles long. Local agencies in Washington State have many more steel trusses on their systems, adding to the inventory of trusses statewide. Many of the trusses have drop spans, a camel back feature to an otherwise continuous truss, to two and three hinged arch trusses sometimes made continuous. With a team of four engineers dedicated to evaluating the rating capacity of WSDOT's inventory of over 3500 bridges, this task is rather daunting and required additional forces be utilized. With a typical bay space of about 40 feet and two or three chords of nodes to analyze, this provides about 10,000 gussets to evaluate for WSDOT, and about the same amount for local agency owned bridges in Washington. This justified a quicker method be used to identify problem gusset locations.

Triage Plan

"Triage" is a natural description of the goals of this evaluation method. Triage is a term used by medical professionals as a means to quickly identify which patient can be saved and which cannot, in hopes of saving the most lives the quickest, or quickly identifying which direction the medical professional ought to continue with a patient to quickly find the problem areas before the problem worsens. This gusset triage is sort of the same thing; a quick evaluation process used to determine where the problem areas are, not necessarily the degree of the problem. Like the term used for in medicine, it's not the most precise evaluation but quickly gets closer to the root of the problem, or as with the medical example, quickly identifies where attention ought to be given and which areas can simply be ignored.

The common analysis methods previously available were the "FHWA Method" (2), procedures outlined within the Manual of Bridge Evaluation Method (3), comparing the loads within the bridge to the capacities determined with the capacities in the AASHTO LRFD Bridge Design Code (4), and any other more refined method an engineer might chose to use, perhaps a finite element model. But all of these methods require a lot of analysis and quickly become cumbersome, especially for the analysis of a truss gusset plate, an item believed through years of experience not to be a problem. So WSDOT developed a new method intended to simplify the analysis, yield results that fairly determined if a gusset had sufficient strength, and brought attention to those gussets that might need more attention using one of the more refined methods. The triage method was calibrated to be somewhat conservative, assuring that an evaluation with this method would not allow a gusset to be inaccurately be deemed inadequate if evaluated with a more precise method.

For the triage method to be most fully utilized, it must be applied to a bridge that has an otherwise complete load rating. More on that below.

A reasonable analogy to understanding the levels of analysis is a sieve stack used for geotechnical investigations. The assumption here is that the reader is familiar with a sieve analysis. Consider a sieve stack with three sieves and a pan at the bottom of the sieve stack. Now consider metaphorically pouring a bucket of bridges into the sieve stack with the expectation of the level of analysis and level of conservativeness in that analysis required to determine a gusset's capacity would be determined by which sieve caught the bridges as they trickled through the sieve stack. The higher level of analysis would be lower in the sieve stack with a finer mesh representing a finer level of analysis. The first sieve would be the Triage Method described below, the second sieve would be FHWA Method, the third would be some more refined method such as a finite element model, and the pan would be the leftovers. Now let's consider how a specific bridge would fall through the entire sieve stack.

If the bridge is analyzed with the triage method, the first sieve, and the Rating Factors (RF) were higher than the RFs for the rest of the bridge, then the gusset rating is complete and the concerns with the gussets are no more. If the RFs are less than that for the rest of the bridge, the engineers sharpen their pencils, evaluate the gussets with RFs lower than the rest of the bridge with a more accurate method, sieve two, and get a more accurate account of the gusset's capacity. If the gusset RF is now higher than the RFs for the rest of the bridge, then the analysis is complete. The process is repeated until the engineer adds additional levels of analysis until they're satisfied the gussets will not control the rating, or until the RFs for the gussets are conclusively deemed to be the critical point; the pan at the bottom of the sieve stack. For this last condition, it takes a lot of analysis, and almost every time, the gussets are deemed adequate with the triage method. And if the analysis goes to the most refined level, you've found your "needle in the haystack."

Research History

WSDOT consulted with researchers at the University of Washington (UW) to determine how this new triage method would look and develop a spreadsheet that could be used on all trusses to locate the problem areas. The results of this research are available in a reference at the end of this report (1). Some of the simplifications are described below.

First of all, it's important to reconsider that there are a lot of bridges to evaluate and a small team of engineers responsible for managing the task of rating so many of them. So one aspect of the research included a standardized spreadsheet for making all triage evaluations fit into the same mold. This allows not only the analysis to be rapid, through the simplified approach within the spreadsheet. But it also allowed for rapid review and acceptance of the work from a host of engineers performing the task, by a few engineers responsible for assuring the task's completion. This small team hired engineers in WSDOT's Bridge Design Section, and many engineers in the private sector to perform much of the work. Each engineer is prone to think and document their work differently, and look at things with their own unique perspective, displaying a bit of the art of engineering. This standardized format sort of homogenized this art and generated a consistent, coherent set of calculations that could be quickly deemed adequate or not. A careful engineer will understand how the spreadsheet works and adjust the few variables the spreadsheet offers to get a desirable result when the limited inputs do not completely reflect a specific situation. More on that is below.

The simplifications of the triage method are evident in the few number of user inputs into the spreadsheet, when compared to other methods. The results made by these fewer inputs were tested and compared to finite element models and the FHWA Method. In the UW research report (1) they demonstrated that these fewer inputs provided consistently conservative results and never produced an unconservative result relative to the parameters that the researchers considered.

The simplifications are briefly described here. To fully understand the extent of the simplifications, the reader ought to study the report published by the UW. Analytically, the Triage Method was based upon a "first yield" limit state, and ensured to be conservative when compared to the limit states in the MBE (3). The research concluded that gusset plate buckling, shear failure, block shear, and other MBE gusset plate limit states all occurred at loads larger than those caused initial gusset plate yielding, supporting the triage method as a conservative analysis tool (1). Furthermore, a simplification with the triage method is it can be used with an envelope of load configurations rather than concurrent loads.

There are three main failure modes considered, yielding of the gusset in tension or compression, buckling of the gusset in compression, and rivet shear.

First of all, fracture was not considered as a viable failure mode because yielding and buckling always developed before fracture for the cases studied in the UW Report.

Yielding: Yielding was evaluated as if the stresses were always along the principle axis. This was done to make allowance for overlapping stresses due to multiple members loading the same gusset. Holes in the gusset were considered by limiting the maximum stress in the gusset to its yield stress divided by the square root of 3, reducing the strength of the gusset.

Buckling: There were many methods considered for modeling buckling. The modified Thornton Method was used with a K factor equal to 1.0. This was the least conservative method considered, yet still provided acceptable results within the parameters of the research. In the research, gusset buckling was never found to occur prior to the onset of first yielding. The Triage check was found to control over buckling in all compression members.

Rivets: The rivet capacity check was not redefined or modified as a result of the triage method development. Rivet shear checks were done by simply determining the capacity of a rivet based upon the material's yield strength and multiplying it by the number of rivet shear planes. Rivet shear strength was determined based upon material strength and connection length (3), if the engineer chose to consider connection length.

Some items are not fully understood or developed. Corrosion requires quite a bit of engineering judgment in order to correctly modify the user inputs. Stacked gussets also are not included in the user inputs and modifications need to be made to the input for this case as well. The engineer would be wise to document how they adjusted the inputs to get the result they sought in order to speed up approval and provide thorough documentation of their work, since the adjustments may not display themselves as plainly for their case as they would for a more usual case.

Modeling Methods

The focus of the modeling effort is simply to find the axial forces within the main members assuming pinned ends just as the bridges were originally designed. This can be done by utilizing an old load rating, or creating a new model of the bridge. Most bridges on WSDOT's inventory were rated using software not immediately available, or not familiar to newer engineers. It's been common for an engineer to generate their own model using software used in new bridge design.

The bulk of this task was performed by engineers who routinely design new bridges. With the nature of bridge design and the attention to detail a new design gets, the first hurdle in modeling to cross was deciding to use a two or three dimensional model. After numerous three dimensional models of varying complexities were evaluated and compared to two dimensional models, the two dimensional model was eventually accepted by many of the engineers working on this task. The two dimensional model combined with lane load distribution factors gave excellent results for the triage method. However, on one occasion a three dimensional model was utilized for a bridge repair after being rated. The value this three dimensional model offered the team designing the repair is up for dispute as it did create a valuable tool for the repair, but did require extra work for the gusset rating. Regardless, the two dimensional model is the quickest simply for the task of rating gussets.

It's important for an engineer to understand how trusses function and how they were evaluated when they were designed. A fully fixed model can often give different results than a model with pinned member ends. In a pinned truss, for example, some connections with identical member arrangements will have identical forces. This is the case for hanger members supporting only a floor beam. With the moment transfer through connections in a fully fixed model, in some cases this was not the case. If this is not the case, something is wrong or the structure is not behaving as the engineer assumes. Another example is understanding how forces flow through the structure for dead load. An engineer ought to consider a truss as a very deep beam. If a beam were loaded with a uniform load, configured with the same span arrangement of the truss, then the moment and shear patterns of the beam ought to be reflected in the chords and web forces of the truss. Chords generally resist the moment portions within the equivalent beam and the diagonals generally resist shear. The chords ought to have higher axial forces where moment in the equivalent beam would have higher moments, and the diagonals ought to have higher axial forces where the equivalent beam has high shear. And then when live loads are applied, there ought to be similar force patterns in the axial force envelopes.

A unique aspect of rating trusses for older trucks is a moment and shear rider used in the HS-20 Loading (3). Along the lines of the discussion above, the question arises regarding how to apply the moment and shear riders. Since chords generally take moment in the truss, when compared to an equivalent beam, they would consider the axial force effects of the moment rider. By the same logic, the diagonals would receive the force effects of the shear rider. The maximum force effect of these riders would be compared to the truck for the HS-20 load.

Example

An example to consider is a bridge at Vantage, Washington. The bridge is located 136 miles east of Seattle, Washington along Interstate 90 where it crosses the Columbia River. The truss portion is a 1170' continuous camel back truss, see Figure 1. We'll consider Node L4, see Figures 2 and 3. The intent of this report is not to teach the reader how to perform the triage evaluation process. It's simply intended to demonstrate the value of the triage method in global terms. So listed below are some of the highlights of the calculations and how the results of this analysis were applied.

On a side note, while this paper was being written a new method was approved by AASHTO as a ballot item. That ballot item is not addressed in this example. It is discussed further in this report in a separate discussion. (7).

Figure 1 ~ I-90 Vantage Crossing

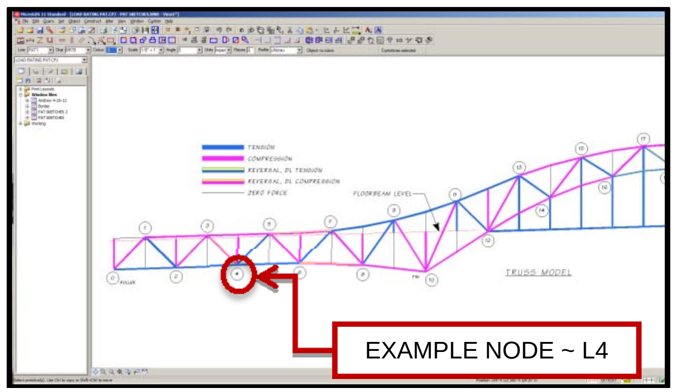

Figure 2 ~ Force Pattern

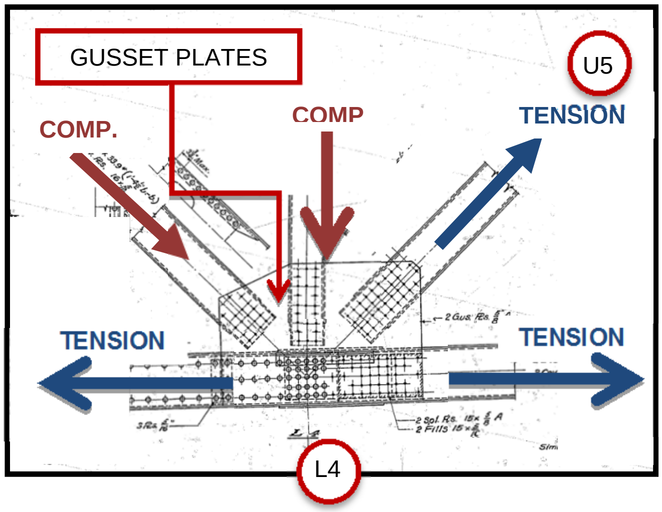

Figure 3 ~ Node L4

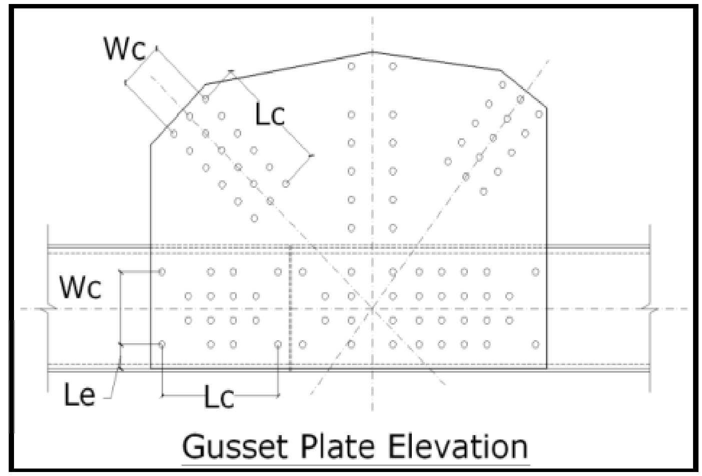

Figure 4 ~ Triage Input

LOAD TYPE	TRIAGE INPUTS Tension (kips)	Comp. (kips)	LEGAL IN OTHER LANES FOR OL IN RIGHT T. (kips)	C. (kips)	L4-U5 ~ Inventory Resistance Type Yielding	Buckling	Rivets	GUSSET SUMMARY	REMAINDER OF BRIDGE
Dead	314.7				RF	RF	RF	RF	RF
HS-20	81.9	-71.0	54.7	-35.7	2.70	N/A	1.86	0.92	0.31
TYPE 3	35.2	-42.6			6.28	N/A	4.32	1.45	1.10
TYPE 3S2	46.4	-55.1			4.77	N/A	3.28	1.38	1.05
TYPE 3-3	49.1	-58.2			4.50	N/A	3.10	1.47	1.12
NRL	53.9	-64.2			4.10	N/A	2.82	0.92	NA ~ Pre 2011
LEGAL LANE	56.4	-58.4			3.92	N/A	2.70	1.50	1
OL1	65.2	-30.1	NOTE:		10.56	N/A	6.93	1.72	1.08
OL2	118.5	-53.2	OL for triage input		5.82	N/A	3.82	1.38	0.92

Table 1 ~ Load and RF Summary

Table 1 shows the forces in Member L4-U5, RFs for this gusset, and the minimum RFs for the rest of this bridge. Figure 3 shows the node geometry for our example. Figure 4 shows some of the input values used to analyze this connection. Notice that for the current load rating, the NRL Truck was not checked. This was a new requirement in 2011. Evaluating the remainder of the bridge for the NRL truck is beyond the scope of the triage method and will be accounted for when that rating is updated.

Figure 2 shows the force pattern in half of the truss. Since the bridge is generally symmetric, the force patterns are mirrored for the other half of the truss. Notice the tension in the top chord members over top of the interior pier, and compression in the corresponding bottom chord members. Also notice the tie and middle chords are completely in tension in the “camel back” portion near the mid-span of the truss. This is reflective of an equivalent three span continuous beam discussed above with the same spans as this truss.

Figure 3 shows more localized forces near Node L4. Notice Member L4-U5 is in tension. Furthermore notice that the vertical member, L4-U4, is in compression, as is every other vertical similar to it in Figure 2. Without the floor beam loads, this would be a zero force member due to the truss geometry at Node U4. The floor beam is the only member acting on this vertical and the others like it. Therefore every vertical member like this ought to have the same forces. And that is the case for this truss model.

In Table 1, you can see the triage method produced RFs for yielding and rivets, but not for buckling. Had this member been in compression, there would be RFs provided for buckling as well. You'll also see this connection did not control the gusset rating, and that the overall rating was not controlled by the gussets.

In Figure 4 you can see the simple inputs used to define the geometry of the connection of the diagonal member. Within the spreadsheet, material strengths are defined elsewhere, and there is room to be very precise with those. But as Figure 4 shows, the geometry definitions are greatly simplified, adding much of the value of the Triage Method.

Application

We can conclude from the example above that the gussets on this bridge do not control the load rating, and this gusset evaluation is complete. The failure modes addressed in the research do not control the rating. As described above, had the triage method yielded lower rating factors, then the level of analysis would have increased until the gussets were deemed not controlling, or proven to control the rating. As for the overall task of rating every gusset plate in Washington State, this bridge is complete and the engineer should progress onto the next bridge.

The Next Steps

If the gusset rating processes happen to find that metaphorical "needle in the haystack" mentioned above, then disaster could be averted. A bridge might be closed before heavy loads are put on it, or it might get repaired. In the extreme case, lives would be saved and bridge spans improved and preserved.

A thorough analysis of a gusset plate's capacity will bring about new attention to gusset repairs or strengthening. If a gusset were to be deemed the controlling point of a bridge, or if another part of a bridge is strengthened, more data will be available to determine of the gussets ought to be considered in those strengthening measures.

Engineering assignments and bridge inspections will be different. With national attention turning to preserving infrastructure instead of replacement, gusset rating follows current design trends. Engineers will likely see more of this type of work, or better prepare themselves for an inevitable bride repair.

For the remainder of a truss bridge's life, or until rating policy changes, the gussets will continue to be rated in this fashion. The gusset rating will continue to be a part of the rating package and remain on record. More attention will be given to gussets in bridge condition inspections. WSDOT is verifying thickness and confirming or correcting their records, recognizing that as-builts might not always precisely reflect the true as-built condition.

2013 AASHTO Agenda Item T18-4

The method outlined in the 2013 AASHTO Subcommittee on Bridge and Structures, T-18 Bridge Management, Evaluation, and Rehabilitation, Item T18-4 has not been included in the Triage Method discussion. This method was developed, or at least brought to the industry's attention after the Triage Method was adopted by WSDOT. However the Triage Method does provide another analysis tool to consider. In the sieve analogy earlier in this paper, this would constitute another sieve for bridges that are not deemed adequate with the triage Method. Outlined below is some discussion on this method, and how it compares to the Triage Method.

This method nearly applies common "design" methods and checks to the rating effort. The methods are somewhat modified from usual design methods for reasons beyond the scope of this paper. There are more failure modes for the engineer to consider, and precise accommodations made to consider the effects of corrosion. Some of the failure modes are shear across planes parallel to members, block shear, rivet bearing, and partial plane shear yielding. While it's not the intent to instruct the reader how to use either of these methods in great detail, listed below is some explanation as to how some of these failure methods are addressed in the Triage Method.

Block shear is not checked in the Triage Method because it was calibrated to assure block shear would not be controlling failure mode. Rivet bearing and slip resistance is not checked in the Triage Method because rivet strength is based upon empirical data developed from fully connected joints, which includes the interaction any component would contribute to strength. In the T18-4 Method, specific instruction is given to account for corrosion. In the Triage Method, accommodations for corrosion are determined by the engineer and documented for approval by WSDOT's Load Rating Engineer.

The T18-4 Method is expected to remain another viable method for evaluating gussets, and there is no plan to incorporate it's components into the Triage Method. It has been adopted and is expected to be written into the Manual of Bridge Evaluation (3) in future editions.

Conclusion

"….The colossal disasters that do occur are ultimately failures of design, but the lessons learned from those disasters can do more to advance engineering knowledge than all the successful machines and structures in the world." This is a quote from Henry Petrosky in his book, To Engineer is Human (6).

While gusset load rating was born out of a colossal disaster, it has brought attention to a genuine need in the preservation and usage of truss bridges. And with such a long track record of successful trusses and a long time simply ignoring gusset plates, we're advancing our body of knowledge of the structures we all use so effortlessly and frequently.

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There are even still more methods, more checks, and a broader understanding of what an engineer ought to consider when evaluating gusset plates since WSDOT developed the Triage Method. For the needs at WSDOT, this method still provides a rapid evaluation tool to identify major problem areas quickly. It also makes a valuable contribution, advancing the body of knowledge and science available to the engineering community as all of us sort out how to address this newly discovered area of concern on our aging highway system and protect those we wish to serve with our steel truss bridges.

References

(1) Berman, J.W., Wang, B., Roeder, C.W., Olson, A.W., Lehman, D.E, *Triage Evaluation of Gusset Plates in Steel Truss Bridges*: University of Washington

(2) FHWA Publication FHWA-IF-09-014, February 2009

(3) AASHTO Manuel for Bridge Evaluation, LRFD First Edition, 2008 and interims through 2010

(4) AASHTO LRFD Bridge Specifications, Fifth Edition, 2010

(5) NTSB/HAR-08/03 PB 2008-916203, Notation 7975C, November 14, 2008

(6) Petroski, H., (1992) "To Engineer is Human."

(7) 2013 AASHTO Subcommittee on Bridge and Structures, T-18 Bridge Management, Evaluation, and Rehabilitation, Item T18-4