

# **Failure in Structural Steels and Overview of I-35W**

## **Bridge Collapse**

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### **Introduction**

Research into the study of the collapse of steel bridges has become popular with the recent I-35W bridge collapse in Minneapolis, Minnesota. An example of this research is performing a failure analysis that would be necessary to determine how preventative measures can be taken in the future to prevent similar bridge collapses. Such an analysis should review previous failures in steel bridges and attempt to apply them to existing or future bridges. This can be accomplished by examining the possible methods of failure in individual members in existing or future bridges as well as the impact on surrounding members and ultimately the entire system if one member were to fail. However, before such analysis can begin, it is necessary to obtain proper knowledge about steel and different methods of failure in steel. This paper will begin by examining the properties of steel, including its formation, standards, and use in construction. Next, it will discuss various forms of fracture in steel including ductile, cleavage, and intergranular fracture. This section will be followed by the description of particular steps in the failure analysis process. Finally, the paper will conclude with a brief overview of the design and the failure of the I-35W bridge, as well as the socioeconomic impact the collapse had on the city of Minneapolis.

# Steel Properties

## Formation of Steel

The most commonly used steel in construction is carbon steel. On the molecular level, these constructional steels are made up of a combination of iron (Fe) and carbon (C) with varying amounts of other elements that include manganese (Mn), phosphorus (P), sulfur (S), silicon (Si), and copper (Cu). It is much preferred for the majority constructional steels that are produced to be made up of almost entirely iron and carbon, but the other elements are essential to produce an effective alloy. An increased proportion of carbon is especially important because it decreases ductility and toughness and makes it more difficult weld. However, an increase in carbon also increases overall strength and hardness, thus making high-carbon steel i.<sup>1</sup>

The formation of steel is a long process. Since steel is mainly made up of iron, great quantities of iron must be removed from its ore minerals, magnetite and hematite. This is done through a process called smelting, where the iron ores are put into a blast furnace that produces a heavy molten iron called pig iron.<sup>2</sup> This is then a part of ingot casting, which is the most common manner of forming steel. The process begins by pouring molten steel with a particular desired chemical composition into castings. The steel solidifies with almost exactly the same chemical composition as the molten steel on the outside, but the rate of solidification decreases the farther inside the steel. On the inner parts of the steel, crystals of relatively pure iron solidify first and the other elements in the composition solidify separately. This leads to a higher number of deficiencies and deformations on the inner part of the steel. These deficiencies and deformations can be either microscopic cracks or impurities within the alloy's structure. They are particularly

high along the axis through the centroid of the steel. Such problems in steel can decrease strength and make it susceptible to excess cracking and even fracture.<sup>3</sup>

However, a technique called rolling helps spread out interior deformations and helps promote ductility and toughness. This technique is used in the creation of almost all carbon steels used in construction. The process of rolling involves squeezing a steel ingot between two rolls revolving at the same speed but in opposite directions. This reduces the cross-sectional area and increases the length of the steel. After a few passes with the rollers, a small part at each end of the steel is cut off to eliminate lower grade steel. The products of this initial rolling are blooms, billets, or slabs, which are then finished into whatever type of steel product is needed via more rolling.<sup>4</sup>

## **Standards**

The American Society for Testing and Materials, or ASTM, provides standards regarding the composition, strength, and elongation requirements of different types of materials that must be followed in design and construction. In this paper, the knowledge of the ASTM standard for A36 carbon structural steel is necessary since A36 steel refers to “carbon steel shapes, plates, and bars of structural quality for use in riveted, bolted, or welded construction of bridges and buildings, and for general structural purposes.” ASTM specifies that the chemical composition of A36 steel is .26% carbon (C), .40% silicon (Si), .20% copper (Cu), .05% sulfur (S), and .04% phosphorous (P), with trace elements of manganese (Mn) and the rest of the composition being iron (Fe). In tension testing for plates, shapes, and bars, A36 steel must have a tensile strength of 58-80 ksi, or 400-550 MPa, and a yield point of 36 ksi, or 250 MPa. The elongation in 8 in, or

200 mm, must be a minimum of 20% for all shapes, and the elongation in 2 in, or 50 mm, must be a minimum of 23% for plates and bars and a minimum of 21% for shapes.<sup>5</sup>

The knowledge of the ASTM standard for A992 structural steel is also necessary since A992 steel refers to “rolled steel structural shapes for use in building framing or bridges, or for general structural purposes.” ASTM specifies that the chemical composition of A992 steel is less than .23% carbon (C), between .50% and 1.50% manganese (Mn), less than .40% silicon (Si), less than .15% vanadium (V), less than .05% columbium (Nb), less than .035% phosphorus (P), less than .045% sulfur (S), less than .60% copper (Cu), less than .45% nickel (Ni), less than .35% chromium (Cr), and less than .15% molybdenum (Mo), with the rest of the composition being iron (Fe). In tension testing for any kind of use of A992 steel, the tensile strength must be 65 ksi, or 450 MPa, and the yield point must be between 50 and 65 ksi, or between 345 and 450 MPa. The elongation in 8 in, or 200 mm, must be a minimum of 18%, and the elongation in 2 in, or 50 mm, must be a minimum of 21%.<sup>6</sup>

The final standard that is important in this paper is that for A592 high-strength quenched and tempered low-alloy steel. This is important because A592 steel refers to the steel that is used for “forged fittings and parts for pressure vessels.” The chemical composition specified by ASTM for A592 steel varies for different grades of the steel. For Grade A, ASTM specifies that the chemical composition is between .15% and .21% carbon (C), between .80% and 1.10% manganese (Mn), less than .025% phosphorous (P), less than .025% sulfur (S), between .40% and .80% silicon (Si), between .50% and .80% chromium (Cr), between .18% and .28% molybdenum (Mo), between .05% and .15% zirconium (Zr), and less than .0025% boron (B),

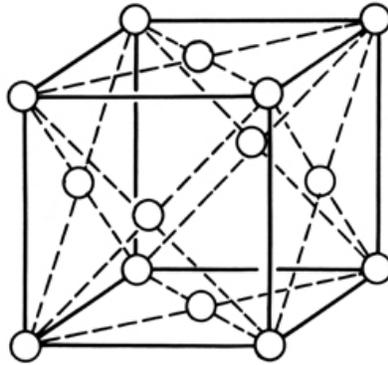
with the rest of the composition being iron (Fe). For Grade E, ASTM specifies that the chemical composition is between .12% and .20% carbon (C), between .40% and .70% manganese (Mn), less than .025% phosphorous (P), less than .025% sulfur (S), between .20% and .35% silicon (Si), between 1.40% and 2.00% chromium (Cr), between .40% and .60% molybdenum (Mo), between .04% and .10% titanium (Ti), between .20% and .40% copper (Cu), and between .0015% and .005% boron (B), with the rest of the composition being iron (Fe). For Grade F, ASTM specifies that the chemical composition is between .10% and .20% carbon (C), between .60% and 1.00% manganese (Mn), less than .025% phosphorous (P), less than .025% sulfur (S), between .15% and .35% silicon (Si), between .70% and 1.00% nickel (Ni), between .40% and .65% chromium (Cr), between .40% and .60% molybdenum (Mo), between .03% and .08% vanadium (V), between .15% and .50% copper (Cu), and between .002% and .006% boron (B), with the rest of the composition being iron (Fe). In tension testing for any kind of use of A592 steel, the properties differ for different lengths of the steel. For lengths of less than 2.5 in, the tensile strength must be between 115,000 and 135,000 psi, or 795 and 930 MPa, and the yield strength must be at least 100,000 psi, or 690 MPa. The elongation in 2 in, or 50 mm, must be at least 18%, and the reduction of area must be at least 45%. For lengths of between 2.5 and 4 in, the tensile strength must be between 105,000 and 135,000 psi, or 725 and 930 MPa, and the yield strength must be at least 90,000 psi, or 620 MPa. The elongation in 2 in, or 50 mm, must be at least 17%, and the reduction of area must be at least 40%.<sup>7</sup>

### **Use in Construction**

Utilizing steel in construction has definite advantages over other materials. Steel has a high strength, and can have a high stiffness and a high ductility at the same time. Added advantages

are that steel is theoretically uniform in strength and has a high strength per unit weight, making the design process much easier. It is also cost efficient because of its ease of assembly once it is produced and at a construction site and because of the fact that it is recyclable. However, there are some definite disadvantages to using steel as well. Steel is particularly susceptible to corrosion by water or other chemicals, which could ultimately lead to failure. The strength and stiffness of steel are greatly reduced when it experiences high temperatures caused by fire. The final disadvantage is the danger of brittle fracture because it can occur suddenly with little or no warning and lead to a total system collapse.<sup>8</sup>

## Fracture in Steels



**Figure 1: Atomic scale diagram of crystal structure of a typical structural steel<sup>9</sup>**



**Figure 2: Microstructure of a low-carbon pipe steel<sup>10</sup>**



**Figure 3: Typical steel I-beam shape at full scale**

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## **Introduction**

Fracture, as it relates to engineering, is the physical separation of a material into two parts or the creation of a void such as a crack in a connecting material. Understanding fracture, and in particular fracture mechanics, is essential in trying to pinpoint possible origins of failure in steel in a structure or in creating a design that helps prevent failure. The best way to provide this accurate assessment is by viewing a material such as steel on the micro-scale. As shown in figure 2, the micro-scale clearly shows the individual grains of the steel. A steel is far more likely to fail along these grain boundaries than it is to fail by bonds breaking on its atomic scale, as shown in figure 1. On the micro-scale, there are three main types of fractures that can occur: ductile fracture, cleavage fracture, and intergranular fracture.

## **Ductile Fracture**

Since brittle cleavage and intergranular fracture are rare occurrences, the type of fracture of most concern in engineering design is ductile fracture. When a material undergoes a stress that is either tension or compression, it also experiences a strain in the corresponding direction of the stress. This strain would reduce the cross-sectional area of the material if it is tension. At a certain point, the material reaches an instability point where strain hardening is slower than the loss of cross-sectional area, causing necking to occur in the material. A perfect material would neck until there would no longer be a cross-section and the total reduction in the cross-sectional area would be 100%. However, this is not a realistic expectation for any kind of material used in engineering design.<sup>12</sup> The majority of materials actually used in construction contain some kind of impurity or impurities.

In general, construction materials contain three different types of particles: precipitate particles, intermediate particles, and large particles. The precipitate particles are purposely developed to be included in the material, giving the material its required yield strength. Intermediate particles can also be essential to the physical strength properties of the material, but they can be slightly more complex in nature. The large particles are complicated compounds of alloying elements that generally have no contribution to the strength properties of the material. The problem with the intermediate and large-sized particles is that they are typically brittle and cannot take any kind of significant deformation due to strain.<sup>13</sup> Thus, these are the impurities that have an effect on the final process of ductile fracture.

Since they do not deform easily, the larger particles, also called inclusions or second phase particles, create voids when a significant strain is put on a material. The voids created by these impurities make up the first stage of the process of ductile fracture. The next stage involves the growth of these voids by increased amounts of plastic strain and hydrostatic stress. The third and final stage is the coalescence of the growing voids and the ultimate failure of the material. This process of void growth in ductile fracture causes a material to reach its point of ultimate failure at a much lower strain than if it was a perfect material.<sup>14</sup>

### **Cleavage Fracture**

Cleavage fracture is the term used for a brittle fracture that occurs in materials at grain boundaries.<sup>15</sup> It often occurs when the local peak stress over a particular length exceeds the cleavage fracture stress of that material. There are three components of a cleavage fracture: microcrack nucleation, start, and growth. Microcracks are commonplace in most materials, and

they have almost no effect on the overall strength and ductile properties in materials such as steel. However, one of two things can happen after the nucleation of a microcrack. The first is that microcrack start is not realized and a microcrack nucleation will have no further effect on a material. The second thing that can happen is, when the initial stages of plastic deformation begin to occur in a material, microcracks may begin to propagate in an unstable manner and a possible fracture enters the stage of microcrack start.<sup>16</sup> When microcracks formed in brittle carbide particles propagate into the matrix of the material, the fracture will enter the stage of microcrack growth and fracture is imminent.<sup>17</sup>

### **Intergranular Fracture**

Intergranular fracture is one possible form of fracture that occurs in steel ingots and castings. The susceptibility of a material to intergranular fracture depends greatly on the chemical composition of the material. Generally, it is caused by the precipitation of AlN from steel rich in nitrogen deoxidized with excessive aluminum. It can also be prompted by increasing carbon and manganese, which would strengthen the grain boundary. However, adding phosphorus and sulfur weakens the grain boundaries and just lowers the chance of intergranular fracture. The susceptibility is also increased by greater size and weight of the castings.<sup>18</sup>

### **Linear Elastic Fracture Mechanics: Critical Overview**

One theory that has been used to explain the brittle-elastic failure of materials is linear elastic fracture mechanics. The study of linear elastic fracture mechanics does not date back to that long ago, mainly because problems with fracture did not bring it to the forefront until World War

II. During WWII, however, fracture emerged as a significant problem in the mass-produced “Liberty” ships used for transporting men and supplies to Europe. In all, 319 cases of serious fracture were reported with Liberty and other types of ships.<sup>19</sup> Since then, there have been several lengthy texts dedicated to understanding the causes and the origins of fracture in materials such as steel.

The theory of linear elastic fracture mechanics upholds that the possible origin fracture in materials is a crack. Fractures due to cracks occur in two stages: crack nucleation and crack growth.<sup>20</sup> Crack nucleation originates due to impurities within the crystal structure of a solid material. These impurities may be a foreign atom occupying a place in the crystal structure, a substitutional impurity, or an atom that is a part of the crystal structure situated in a non-lattice position, an interstitial impurity.<sup>21</sup> The reason why cracks affect a material is because a crack produces a concentration of stress at its tip. This concentration of stress increases with increasing crack length.<sup>22</sup> However, cracking seldom actually leads to a fracture, and there are numerous microscopic cracks within members used in construction that do little to decrease the members’ overall strength. Cracking does lead to fracture through crack growth. This occurs when the stresses at the crack tip exceed a critical value that proceeds to cause extension of the crack. Once a crack has extended beyond a critical length, it will propagate spontaneously until it ultimately produces a cleavage fracture or a ductile fracture.<sup>23</sup> Despite all of this, linear elastic fracture mechanics is simply one possible model that attempts to try to explain fracture.

## **Failure Analysis Process<sup>24</sup>**

After failure occurs in steel, there are several processes that can help determine why it occurred. R. W. Fuller of the Grand Gulf Nuclear Station, J. Q. Ehergott Jr. and W. F. Heard and R. D. Stinson of the US Army Engineer Research and Development Center, and K. Solanki and M. F. Horstemeyer of the Mississippi State University Center for Advanced Vehicular Systems outline these processes as they apply to their failure analysis of a AISI 304 stainless steel shaft. These processes involve 14 steps: observation, information gathering, preliminary visual examination and record keeping, nondestructive testing, mechanical testing, selecting/preservation of fracture surfaces, macroscopic examinations, microscopic examinations, metallography, failure mechanism determination, chemical analysis, mechanical failure analysis, testing under simulated service conditions, and final analysis and report. “This conventional 14-step failure analysis methodology is applicable to complex loading such as the fracture of materials due to overloading or the progressive weakening of a material due to fatigue,” writes Fuller. Thus, an understanding of the use of these steps is important in the overall analysis of a bridge collapse.

An overview of the situation being analyzed is necessary and three steps may be used to help accomplish this. Observation is the first step in the failure analysis process. The authors outline several important observable facts in this step. Some of these observations include the type of material, the time the observed object has been in use, the use of the object, and the temperature of the operational environment. In the case of a steel bridge frame, knowledge of the type of use is especially important because this background knowledge might lead to already known ideas as to why the system may have failed. Another step associated with observation is that of information gathering. The authors indicate that analyzing whether a system was up to design

standards and specifications is essential. In addition, the context of the failure is important to understand. Photographs, witness statements, and knowledge of what was happening leading up to the first sign of failure and afterwards are helpful in this respect. The final step in the initial overview of the situation is preliminary visual examination and record keeping. In the case of the authors, “initial examination included photography, dimensional checks, and possibly preparation of replicas of fractures surfaces.” It is necessary that this process takes place as soon as possible after the failure in the system, because, in cases such as failures of bridges, immediate cleanup of the failure might be necessary based on the demands of transportation and convenience.

The next steps necessary in failure analysis have to do with a close inspection of the fracture material itself. The first step of this is to select which fracture surfaces to analyze and then to preserve those surfaces. In this step, a fractography study is often performed by investigators to identify surface features that may help indicate the type and origin of failure. Some of these particular features include beach marks, river marks, striations, ratchet marks, and chevron marks. Macroscopic examinations and metallography are often combined into one in closer inspection. In this paper, this step involved taking a sample of the material and analyzing its microstructure. The closer examination continues with microscopic examinations. This step uses some type of magnifying device, in this case a scanning electron microscope, in order to conduct a closer examination of the surface. Microscopic examination allows one to more easily identify the particular surface features that could help possibly indicate the type and origin of failure. It is also necessary to perform a step of chemical analysis to better understand the material. In this study, a spectrometer was used in order to determine the chemical composition

of the material. Experimentally determining the composition can help determine if the material matches what the design specifications had originally specified. Certain steps may also need to be performed to determine particular strength properties of a material. The first of these steps is mechanical testing. In the case of this experiment, “hardness testing was performed to determine the strength and strength gradient of the shaft.” Another step to help determine these properties is mechanical failure analysis. Based on the application of and the loads applied to a material, strength properties such as torsional and shear stress may be found.

Once these steps are finished, the final two steps of failure analysis need to be completed. The first of these steps is to determine the failure mechanism of the material. “The primary objective of a material’s failure analysis is to determine the root cause of failure,” writes Fuller. Any kind of failure can generally be contributed to one of four categories: design, manufacturing, service, or material. Using the previously mentioned twelve steps helps to paint a complete picture with which one can help determine what category of failure mechanism a failure belongs to and, more importantly, what specifically caused the failure. The very final step in the failure analysis process is the final analysis and report. This step involves applying the determined failure mechanism to other situations in order to prevent such a failure from happening again. The analysis may consist of different ways to produce a better design, less manufacturing deficiencies, better maintenance of structures, or stronger materials.

## **Case Study: I-35 Bridge Collapse**

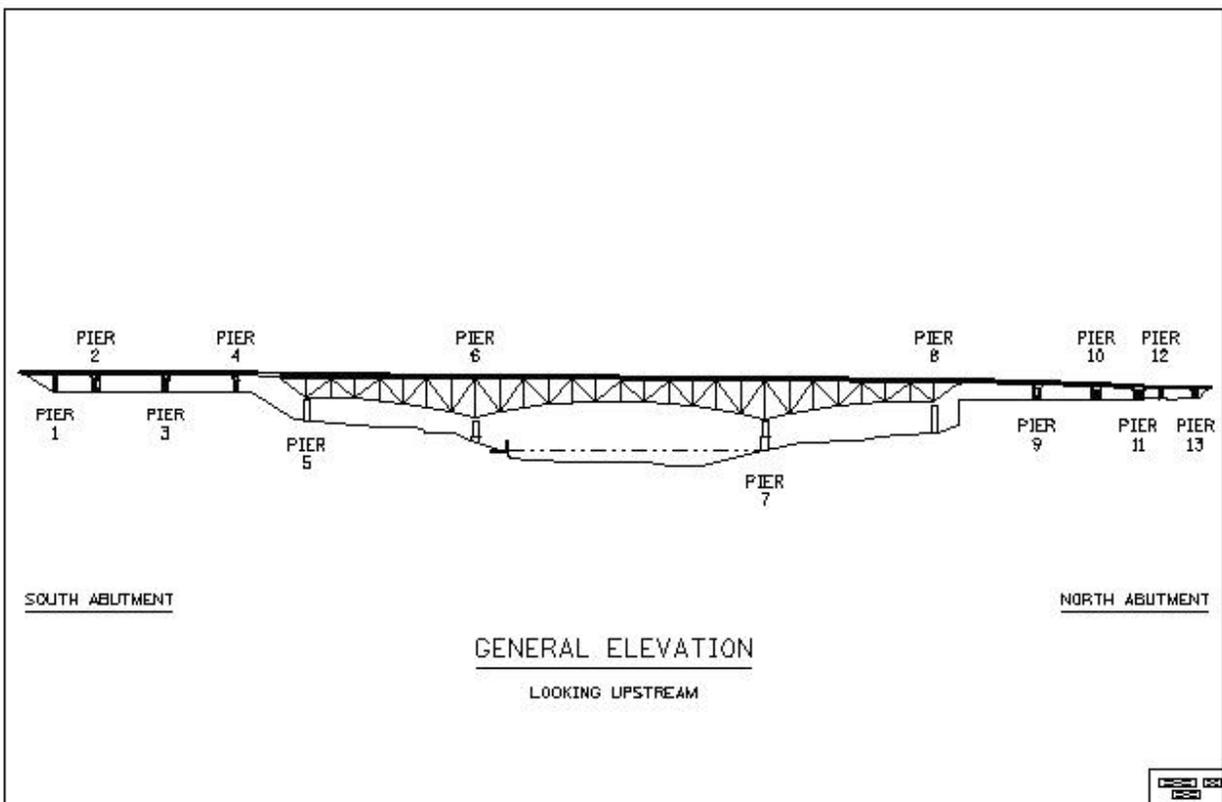
### **Overview**

On August 1, 2007, at about 6:05 P.M. CDT, approximately 1,000 feet of the I-35W highway bridge collapsed. The bridge, spanning the Mississippi River in Minneapolis, MN, was 1,907 feet long and carried eight lanes of traffic, four in each direction. At the time of the collapse, roadwork was being performed and two lanes in each direction were closed. Construction equipment and materials were being stored on the southbound part of the bridge. Also at the time of the collapse, there was a tremendous amount of traffic due to the construction. The combination of the traffic, the concentrated construction loads, and increases in the dead-load of the bridge due to modifications all caused the stress at critical locations in the bridge to be too great.<sup>25</sup>

The engineering consulting firm Sverdup & Parcel and Associates designed the I-35W bridge. The initial foundations were approved in 1964, and the final bridge design plans were approved by the Minnesota Department of Transportation on June 18, 1965. Construction began on the piers in 1964, and the bridge was opened to traffic in 1967. The bridge also met all the specifications and standards for highway bridges of its type at the time of its design. In 1976, average daily traffic over the bridge was found to be 60,600 vehicles. That number more than doubled by a study conducted in 2004, where the average daily traffic was found to be 141,000 vehicles.<sup>26</sup>

## Design

The I-35W bridge was composed of 14 spans with a total length of 1,907 feet. The total length of the bridge can be split up into three parts: the south approach spans, the north approach spans, and the deck truss spans over the river. Figure 4 shows a general elevation of the bridge looking upstream. The south approach spans are the part of the bridge from south abutment to between pier 4 and pier 5, the north approach spans are the part of the bridge from between pier 8 and pier 9 to the north abutment, and the deck truss spans are the part of the bridge from between pier 4 and pier 5 to between pier 8 and pier 9.



**Figure 4: Elevation of entire length of bridge from south abutment to north abutment**

\*Figure courtesy of National Transportation Safety Board (NTSB)<sup>27</sup>

The south approach spans crossed a street and an access road and had a total length of 416 feet.

This part of the bridge was supported by 14 steel girders, spaced at 8 ft. 2 in. intervals, and a

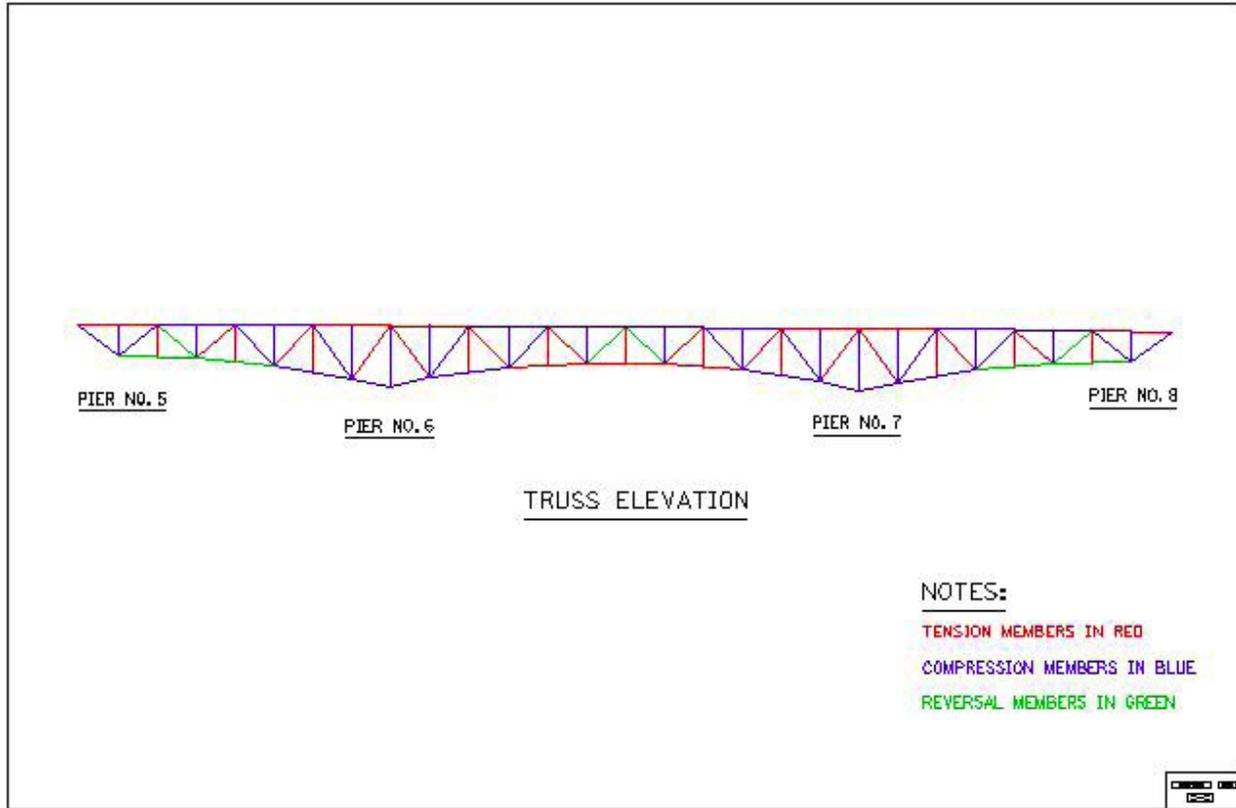
reinforced concrete deck.<sup>28</sup> The girders were curved to accommodate the roadway that made a 3 degree and 15 minute curve<sup>29</sup> or a radius of approximately 1760 feet.<sup>30</sup> Each girder was supported by lateral bracing from steel diaphragms that were approximately 22 feet apart. The girders and diaphragms rested on four concrete piers, labeled piers 1 through 4 in figure 1, and the edge of the south abutment. The north approach spans crossed four lines of train tracks and a large stone retaining wall. Three spans of this part of the bridge were supported by a continuous welded steel multi-girder section, shown in figure 5. The other three spans of this part were composed of a continuous concrete voided slab section. Both of these sections rest on five reinforced concrete piers, labeled piers 9 through 13, with the edge of the voided concrete slab resting on the edge of the north abutment.<sup>31</sup>



**Figure 5: Interior structure of north portion of deck truss**

\*Photo courtesy of National Transportation Safety Board (NTSB)<sup>32</sup>

The main structure of the deck trusses were two Warren-type trusses with verticals that rested on four large bearings.<sup>33</sup> These bearings were supported each supported by a pier that contained two round columns. Pier 5 and pier 8 each rested on footings embedded in rock, while pier 6 and pier 7 both rested on concrete shaft walls. This main structure of the bridge was composed of two identical side-by-side trusses of three spans each. Both trusses were also symmetrical about their center axis and slope downward from south to north for a decrease in elevation of slightly more than 7 feet. The depth of the truss at each end support is 30 feet, varies parabolically to 60 feet at the two interior supports, and again varies parabolically until it reaches a depth of 36 feet at the center point of the main span. Each truss was divided into 28 panels, all of which are exactly 38 feet in length, with transverse welded floor trusses connecting the two trusses at each of these locations. Vertical members are also located at these points extend the entire depth of the truss at their respective locations. Every panel also has a single diagonal member that extends from opposite corners of the panel. The orientation of these diagonal members are changed each panel so that they form a series of Warren-type triangle shapes along the lengths of both trusses. Finally, there are members on the top and bottom of each panel.<sup>34</sup> Figure 6 shows the elevation of the deck truss design, as well as which members of the deck truss are in tension, which members are in compression, and which members experience both.



**Figure 6: Tension and compression members of the deck truss portion of the I-35W bridge**  
 \*Figure courtesy of National Transportation Safety Board (NTSB)<sup>35</sup>

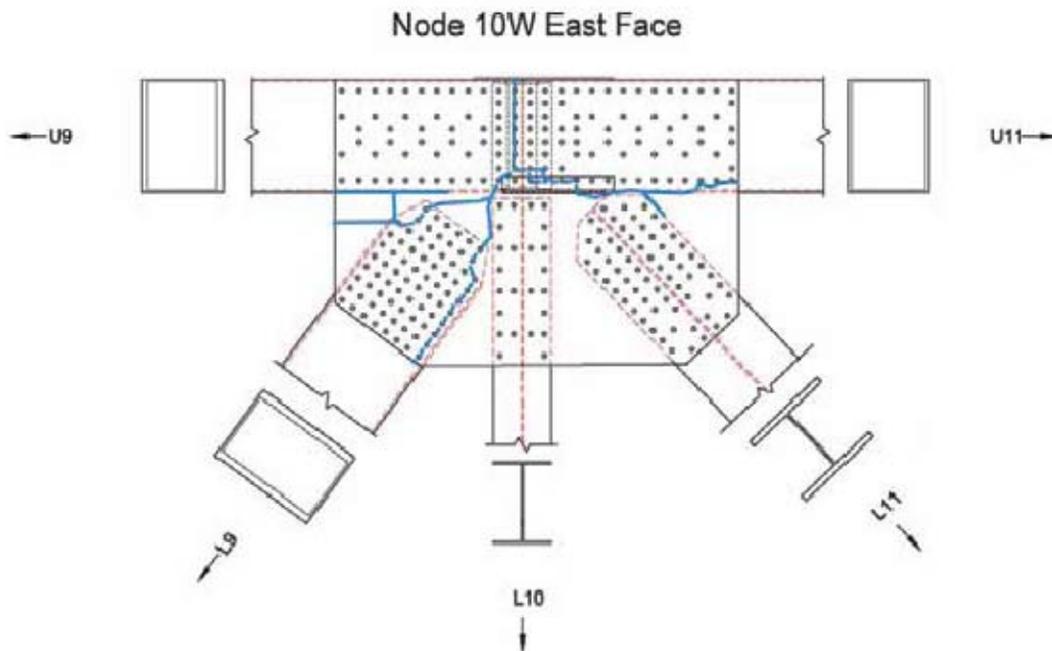
The deck truss was made up of different types of members. The individual horizontal members, called chords, were welded box sections that were 28 inches deep by 21 inches wide. The diagonal and vertical members that were in compression were also welded box sections, but the diagonal and vertical members that were in tension were welded I-shapes. In order to connect these members at a connection point, the truss chords, verticals, and diagonals were all riveted to large gusset plates that varied in thickness from ½” to 1”.<sup>36</sup> These gusset plates connected members at 112 different nodes on the deck truss portion of the bridge. There were two gusset plates at each node, or connection point, with one gusset plate on each side of the node. They were riveted to the side plates of the box members and the side plates of the I-shaped members. However, at some locations, bolts were used instead of rivets in order to facilitate construction.<sup>37</sup>

## **Conclusions Drawn from Collapse**

In the initial stages of the collapse, the center span of the bridge fractured and broke off from the rest of the deck truss structure. The deck truss portion as a whole separated into three large sections, with the center span falling into the river and parts falling onto land north and south of the river. After studying video and physical evidence, investigators concluded that breaks in the center span first occurred just north of pier 6 (see figure 4). Shortly after this, breaks occurred in the center span just south of pier 7. These two critical failures caused an entire collapse of the center span of the bridge, which in turn caused a total system collapse of the rest of the bridge.

In the fracture area just north of pier 6, it was found that all four of the gusset plates at a node were fractured due to fatigue cracking and overload. This eventually led to a cleavage fracture. The fracture pattern from one of the gusset plates is shown in figure 7. Upon fracture, two diagonal members and two upper chord horizontal members separated from the rest of the members at the node location. The loss of structural support due to this separation caused structural deformation to begin in the deck truss south of this location. This led to a chain-reaction of overloading by either compression or tension, thus causing several structural members to fracture as well. The failure of the southern part of the middle span caused a similar failure process in the northern part of the middle span just south of pier 7. A node at this location also experienced fracture in all four gusset plates that connected the structural members together due to fatigue cracking and overload, causing a cleavage fracture. Once again, this overloaded several of the structural members, causing them to fracture due to too much tensile or compressive stress. These fractures caused a total separation of the center span of the bridge,

allowing it to fall into the river. With this entire segment of bridge missing, other sections of the bridge could not support themselves and collapsed as well.<sup>38</sup>



**Figure 7: Inside east gusset plate at node U10W showing similar fracture patterns**

\*Figure courtesy of National Transportation Safety Board (NTSB)

The National Transportation Safety Board (NTSB) concluded that the initial event causing the collapse was a lateral shifting instability of the upper end of a diagonal member in the southern portion of the center span. Another conclusion reached was that the failed gusset plates where the collapse initiated were inadequate to support the structure as the bridge was originally designed, let alone modifications and renovations that were made. This inadequacy was attributed to an error by the design firm that was not caught by government inspectors and other forms of design checks, even though they had several opportunities. NTSB also concluded that the total collapse of the deck truss was likely once the gusset plates failed since the deck truss portion was designed to be “non-load-path-redundant.”<sup>39</sup>

## **Socioeconomic Impact of Collapse**

As previously mentioned, the I-35W bridge in Minneapolis, Minnesota, carried an estimate of 141,000 vehicles per day. The absence of such a major artery of traffic for the city had a tremendous impact on traffic patterns and the local economy. A Minnesota Department of Transportation study concluded that the costs for commuters to find new ways to get to downtown Minneapolis were \$400,000 per day. There were also several additional costs caused immediately by the collapse. The replacement bridge for the I-35W bridge, called the St. Anthony Falls bridge, had an estimated cost of between \$300 and \$350 million as of June 2008. In addition to that, the Minnesota legislature approved a \$38 million bill as compensation to everyone who was on the bridge at the time of the collapse.<sup>40</sup>

The I-35W bridge collapse also had a tremendously negative impact on the local economy. Several small businesses in Minneapolis suffered because the absence of traffic flow that usually crossed the bridge has stopped many customers from frequenting those businesses. Some of these businesses reported losses in revenue of up to 50%. Economic Injury Disaster Loans offered a chance for businesses to hold themselves over until the new bridge was opened.<sup>41</sup> However, these were unsuccessful in helping Minneapolis businesses maintain profits. By June 2008, the loss to Minnesota's economy was approximately \$60 million.<sup>42</sup> Businesses have recently started to see some relief, however, because the St. Anthony Falls bridge opened for traffic on September 18, 2008.

## Conclusion

This paper has established a basic understanding of certain important aspects associated with the analysis of the fracture of steel and its contribution to bridge collapse and possible prevention. Future research will be performed to expand upon this basic understanding and to take a more in depth look into the potential failure that could occur. This research will entail the use of computer models in order to examine the response of a bridge system such as the I-35W bridge to the failure of a connection or the removal of one or more members. A better understanding of structural system behavior under these circumstances may help in the future to prevent other catastrophic failures. It might also help the design of bridges for protection against failure if a sudden blast was to occur, particularly in a possible terrorist attack, and if one or more members were to suddenly fail due to material inconsistencies or poor initial construction.

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