Deterioration of Pin-Connected Bridge Trusses

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ABSTRACT

An important bridge type that marked dramatic progress in crossing large rivers and other terrain obstacles are truss bridges of various configurations. Among them, a distinctive and important class, is the pin-connected trusses built mostly at the end of the 19th and beginning of the 20th centuries. Many of these pin-connected truss bridges are still in place today. Many are gradually deteriorating and getting inadequate for the present-day traffic. Replacement of these trusses is usually prohibitively expensive, often in tens of millions dollars each. Therefore, a good understanding of their vulnerabilities is critical for maintaining them in as good and safe as possible condition. It should also help in optimal decisions about their fate, whether rehabilitation and maintaining, or replacement. This paper describes the historic development, structural work, analysis, and various modes of deterioration of pin-connected trusses. Examples of strengthening and rehabilitation are given. Typical deficiencies and deterioration patterns from numerous inspections of hundreds of pin-connected truss spans are presented.

Key Words: truss, bridge, pins, eyebars, history, deterioration

INTRODUCTION

When trains and automobiles emerged in the 19th Century, they needed stronger and bigger bridges than those for pedestrians and horse wagons. Particularly trains required strong and often long and high bridges, in order to maintain more or less level grade, without rapidly descending or ascending portions. Consequently, significant progress in the construction of bridges took place, especially starting in the second half of the 19th Century and continuing through the beginning of the 20th Century. The development of iron and steel made possible and tremendously facilitated new designs and construction of larger and more reliable bridges. Trusses, particularly pin-connected trusses, became the predominant form of large-span bridges. Still many of these truss bridges exist today and, even though many are fatigued, deteriorated, and brought sometimes to the very limits of their strength and endurance, they continue working and carrying often quite heavy and frequent traffic. Since the deterioration of such old
trusses is naturally progressing, even with good and costly maintenance, there is a growing problem today: what to do with them, and particularly with their older version, the pin-connected trusses.

EARLY TRUSS BRIDGES

In the first half of the 19th Century, there were many designs and patents, notably by Town (1820), Long (1830), Canfield (1833, iron truss bridge), Howe (1840), Whipple (1841), and Pratt (1844). Trusses allowed using relatively short elements, first timber and later iron and steel, in order to construct much bigger overall span length. These trusses used simple, axial tension and compression members, and the corresponding tension and compression material properties rather than bending.

The iron material allowed to achieve much increased span lengths compared to timber; for example Linville build a 320 ft. span over the Ohio River in 1864, and a 519 ft. truss of the Cincinnati Southern bridge in 1876. However, the real progress in building big and reliable truss bridges took place at the end of the 19th Century and continued through the beginning of the 20th Century. It was related to the developments in manufacturing of steel, and specifically the mass production using the Bessemer process. The new material was approximately one quarter stronger than iron and of better quality and homogeneity. At the same time, there was rapid industrial development requiring increased transportation of materials, goods, and people. Bigger, faster, and frequent trains with heavier and stronger locomotives and numerous cars had appeared. Truss bridges were very well suited to serve such traffic and to cross even the biggest rivers (including the Mississippi, Missouri, Ohio, etc.) and other terrain and man-made obstacles. Especially the simple and logically constructed truss followed the natural flow of internal forces such as the Pratt truss, initially pin-connected and later riveted, became the preferred form and most common design between 1885 and 1920 (see Figure 1).

Where the clearance under bridge was limited, the “through” type of truss bridge had a clear advantage; otherwise a “deck” type could be used. The former has its deck supported at the level of bottom chord of the trusses, while the latter has its deck supported at the level of upper chord. The deck truss has less
exposure to being hit by derailed cars or shifted loads as compared to the through truss. However, the structural depth of deck trusses uses significantly more vertical clearance under the bridge. Through trusses allow for more clearance for navigation or other traffic (highway or railway) underneath. However, through truss bridges require special, vertical stabilization of the trusses, and particularly their upper chords, by transverse vertical bracing, called sway bracing. This bracing, along with the portal bracing between the end posts, and the lateral bracing between the top chords creates problems with vertical clearance for the equipment and loads, and sometimes is hit and damaged.

PIN-CONNECTED TRUSSES

The connections in joints of early iron and steel trusses were usually pinned. Later, mostly after the first decade of the 20th Century they became fixed, riveted connections. The pin-connected truss members have the ability of free rotation at their ends and almost perfectly simulate axially loaded members, with only longitudinal forces acting on them. The riveted connections create some bending moments at the ends of members. However, due to rather high slenderness of the members and small transverse differential displacement of their ends, the moments at the ends are small. Therefore, also for riveted connections, it is still possible to assume that the riveted members are loaded with longitudinal forces only. This assumption is well modeled by assuming pin joints for analysis of both pin-connected and riveted trusses. It allows treating the truss as an assembly of simple, axially loaded members arranged in triangles, for geometrical stability.

Some truss members consist of multiple elements, e.g., one diagonal may have four eyebars. This arrangement increases the reliability; similar to that in ropes consisting of multiple wires. In case of imperfection of material, such as cracks, usually only one element of the member is affected. Truss members may be either solid or laced. The lacing allows for lighter weight, but still maintains good stiffness against buckling, and therefore it is often used in compression members, e.g., in intermediate and end-posts and upper chords. The upper chord is continuous over the truss span length, for stiffness and anti-buckling stability. However, the attached hangers/posts may be pin-connected to it, in order not
to introduce harmful bending in the compressed upper chord. The tension members in pinned trusses (bottom chords and diagonals/counters) consist usually of eyebars.

The most common pin-connected truss type is the Pratt truss and variations thereof. A major feature of the Pratt type truss was the usage of a large number of eyebars, tension members, to minimize material which resulted in cheaper spans. One of the unique features of the Pratt truss are the diagonal eyebars installed in the center panel(s) of a truss, in opposite directions one to another (see Figure 2). Under heavy, moving load (sufficiently big to overcome the effect of dead load), the diagonals in center panels could go from tension into compression, depending on from what side the load is approaching the span. For example, in simple, five panel Pratt through truss, the U2-L3 diagonal works in tension under load approaching the center panel from Panels 5 and 4. However, after passing the center Panel 3, the diagonal would go into compression. If it was designed for tension only (as a slender, flexible eyebar), it would buckle under the compression load. Then the whole center panel (now simply a rectangle, pin connected in corners) could drastically change its geometry and become unstable. Then, a failure of the whole truss could easily occur. The remedy for such a danger is to provide a counter bar, i.e. another diagonal bar L2-U3 running in the direction opposite to the first diagonal. By going into tension when needed, the counter provides geometrical stability of the panel and truss. The lack of such counters resulted in some failures of early trusses under heavy moving train loads, before designers and constructors figured it out and used the counter remedy. As stated, under the passing of heavy trains, counters change their stresses back and forth from tension to compression. Consequently, they have a tendency to oscillate. It is often possible to visually notice such oscillation, especially if the members are long. This is normal behavior. This movement may be the starting point for the deterioration of pin-connected trusses.

For increased spanning capability of individual spans and in order to adjust the shape of truss to the natural flow and distribution of internal forces, the upper chord may be made non-parallel to the bottom chord. The Camelback truss has two end posts, two inclined upper chord sections, and a center section parallel to the bottom chord (see Figure 2). The Parker, another form of the Pratt, has chord sections in
an arc such that all upper chord members are of the same cross-section. Even bigger individual spans (without intermediate piers) can be achieved when continuous trusses over piers are used. For purpose of limiting the effect of thermal expansion and to simplify their analysis, bridges of such type can have an “anchor” span which is a truss with cantilevers projecting beyond the piers. These cantilevers serve as supports for additional, “suspended” trusses. The suspended truss can be supported by two such cantilevers (projecting from two anchor spans), or by one cantilever and an abutment or pier (then it is usually named as “semi-suspended” truss). In spite of visually complicated appearance and maze of different members, the structural analysis of such trusses is actually quite simple, even though tedious. In spite of the fact that the anchor span is continuous over the piers, hinges can be assumed at the ends of cantilevers. They offset the static redundancy and continuity of the whole system over the supports and make it statically determinate. Good examples of such, extended trusses with “suspended” spans, are the Harahan Bridge (with the main span of almost 800 ft. length, uninterrupted for navigation) and the Thebes Bridge over the mighty Mississippi River. Bridges of this type have become “workhorses” of bridges, carrying heavy loads over big spans for many years, and still working hard today. Their replacement could run into tens of millions of dollars, so they are basically irreplaceable. Other examples of such monumental type truss bridges are the famous Firth of Forth Bridge in the United Kingdom and the Quebec Bridge in Canada. Some people may say these bridges look heavy and ugly as per contemporary feelings and standards, but others consider them already as an art of significant historic value. Some of them are on the National Register of historic structures and are considered important landmarks. As a good parallel, many considered the 984’ tall lattice tower built from iron and steel by Mr. Eiffel in 1889 for Paris Exposition as an ugly and useless structure. Today it is one of the most powerful and beautiful symbols and tourist attraction in all of France, even though it is essentially useless (and certainly does not carry any trains).

TRUSS ERECTION

The beauty in the use of pin-connected trusses was not only the clear understanding of load paths, but the speed at which the spans could be erected. In a review of photographs of early major pin-connected
truss bridges, it was common to erect falsework between piers, set the span floor system in place and then, using a gantry crane, erect the truss members in a matter of days. In 1890, a 518' long simple span of the Merchants Bridge in St. Louis over the Mississippi River was erected in eight days after the floor system was placed on falsework (see Figure 3).

It is not well known how erectors inserted a pin into a joint. That is no easy task when considering that all the commonly connected members of the joint must align within the \( \frac{1}{32} \) inch pin-pinhole tolerance. To accomplish the insertion, a bullet-shaped steel nose piece was screwed onto the lead end of the pin and the assembly aligned with the common hole for all the joint members. Suspended from a rope tied to an overhead location, a wooden ram would be used to drive the pin into the hole. The nose piece was then unscrewed from the pin end, lomus nuts screwed onto the ends of the pin and the bullet used again at another pin joint.

With pin connected truss member, little remained to be riveted: floor system, laterals and sway frames.

TRUSS DETERIORATION

Initial signs of wear are noted by fretting around pin nuts rubbing against top chord web plates and around the interface of lower pins with vertical members of those pins connecting counters in the span's center panels. At this point in the deterioration sequence, wear is not measurable in the pin joints. As initial wear continues, there is some minor slippage between components on the pins and counter eyebars show a loss of tightness and some wear at their pin connections. With minor wear in the pin joints it may be difficult to determine the amount of wear between component members, but rub marks between components can be used to estimate wear. At this point in the sequence of deterioration, the span remains tight and has a good response to live loads.

As the wear continues in pin connections, gaps appear in vertical members under the lower chord pin; however, the actual wearing surface is on the top contact surface, 180 degrees opposite of the gap.
vertical members, wear at both ends of member pin holes result in a reduced distance between pin joints. This is sufficient to allow primary diagonal member eyebars to loosen. With a moderate amount of joint wear, often the U1 joint (hip joint) flexes, and cracks develop in the upper and lower connection plates. Strengthening by adding straps buys time but is not sufficient to prevent cracks from reoccurring.

With moderate wear in a pin hole of a central panel of the upper chord, the stringer-floorbeam connections of the rigid floor system deflect under the passage of each truck until the full amount of slack is taken out of the joint holes. At first, fasteners fail, followed by cracks developing in the connection angles, and then difficulties develop in maintaining the connections. Associated with moderate joint wear is an interesting observation of top pin joints that have a primary diagonal member and a counter on the same pin. As the live load crosses the span, the counter pushes on the pin and the diagonal pulls on the pin. In due time the pin rotates sufficient to unscrew a nut from the pin. Most nuts have been secured by either checking the threads or by placing a tack weld in the threads but occasionally a pin will back out of the chord web hole.

Continued wear in the pin joints will result in the fracture of fasteners in sway frames which connect between verticals and the top chord. Relative movement between these members will in time fatigue the sway frame connection plates and angles.

Rarely is wear noted in the pin hole of a lower chord eyebars. Wear generally is noted in loss of section of the head from rubbing against vertical members. Some wear may be noted in diagonal eyebar pin holes but generally it may be only enough to be noted by uneven tensioning between bars. However, wear in counter eyebar pin holes may be severe. Scoring of pins occurs primarily at the contact points of vertical members and counter eyebars on the pins. Significant notch scoring may be reason to check stress concentrations.

When severe pin connection joint wear occurs, the truss becomes very loose and excessive lateral motion occurs. There may also be observed a vertical undulation in the top chords which is associated
with the position of the wheels on the span. Cracks will develop in the chords from this action. When severe wear in the pin connections occurs there is a need to slow order trains. Figures 4, 5, 6, and 7 depict sequence of pin joint deterioration from initial stage to severe deterioration.

By the time severe wear occurs, it is too late to re-bore pin holes since the wear results in an oval shaped hole often with a gap approaching ½ inch to ¾ inch, and the first clean hole for a new pin would be too large. Also, the re-boring of pin holes is very expensive and traffic cannot be on the bridge while boring. Installing spider connections to by-pass the pin will work if it is possible for members to be connected together within a joint (no eyebars). The only viable corrective means is to add pin plates to members to stabilize existing pins and engage surfaces of the pin which have not deteriorated.

The loose eyebars associated with the pin connection deterioration can be put into effective work again by flame shortening. The procedure involves extensive preparations, iterative process of several steps of flame shortening in order to equalize the stresses in all bars of each member, and vibration tests to determine stresses in bars before, during, and after the process of shortening. The whole work requires highly specialized skills and strict, careful regiment of work in order not to endanger the structure. It is tedious, time consuming, rather costly, and an art in performing (see Figure 8).

The apparently obvious solution would be replacement of these, often 100 years old or older, bridges. However, there is one, big problem; the high cost of such replacements. Railroads are relatively quick and highly efficient in replacing small, particularly timber bridges, or sometimes even longer ones where there is a possibility of using short, rather inexpensive individual spans. However, when it comes to trusses and especially longer trusses, e.g., 200’, 300’ or longer, where intermediate supports/piers can not be used (e.g., due to navigation), the cost of such replacement runs often into tens of millions dollars per bridge, especially if it is a movable bridge or bridge on high towers. Then, even though the strengthening and rehabilitation of truss bridges is difficult, costly, painstaking, highly specialized, and usually effective only for a limited period of time, such an option always need to be considered first. It may give some precious “breathing’ time, several years or so, for planning, design, and construction of
new bridge. More and more often, the critical path and the longest activity is obtaining sometimes quite
time-consuming permits; especially important in some areas of the country and for old, sometimes historic
structures. In any case, a thorough knowledge of how the truss bridges work, what are the critical areas
and vulnerabilities, and a familiarity with the details of the process of progressing deterioration of trusses
in general, and pin-connected trusses in particular is always very useful for undertaking optimal decisions
about replacement vs. rehabilitation and/or strengthening. Stabilizing pin joints and keeping eyebars tight
extends the life of these pin-connected trusses.
- Almost 25% of all trusses are pin-connected trusses
- Among pinned trusses ~85% are through trusses (TTPs), and the rest, 15% are deck trusses (DTPs)
- The average age of a pinned truss is 96 years and growing
- Over 50% are 100 years or older
Pin-Connected Trusses - Erection

- Falsework simple spans
- Cantilever for long spans
- Simple connections
- Minimize field riveting

Figure 3 – Erection of Pin-Connected Pratt Trusses

- Fretting of some pin nuts, counter eyebars and verticals with adjacent surfaces
- Slippage between components on pin
- Loss of tightness in counter eyebars
- Span tight – good live load response

Figure 4 – Initial Joint Deterioration
Figure 5 – Modest Joint Deterioration

- Counter eyebars loose
- Diagonal eyebars moderately tight
- Minor, measurable gaps noted between some verticals and pins, and in counter eyebar heads
- Few broken fasteners in center of span stringer – floorbeam connections
- Span response to live load - good

Figure 6 – Moderate Joint Deterioration

- Counter eyebars loose to very loose
- Diagonal eyebars several loose, but not in pairs
- Wear noted in most lower chord verticals and some upper chord vertical joints
- Counter eyebar head hole worn and pin scored
- Some upper chord pins shift in position, nuts loosen
- Sway frame fasteners loose
- Stringer – floorbeam connections – cracks, fasteners
- Some looseness felt in truss with passage of live loads
Figure 7 – Severe Joint Deterioration

- Counter eyebars very loose, often slap
- Modest number of diagonal eyebars with unequal tension
- Significant gaps noted in vertical member pin holes, under lower pins
- Hip joint fractures noted in upper and lower connection plates
- Sway frame connections fail
- Stringer – floorbeam connections difficult to maintain
- Undulation in upper chords – member cracks
- Truss response to live loads poor and slow order required

Figure 8 – Flame Shortening of Eyebars

- Used to equalize stresses in groups of bars
- Extensive preparations, strict
- Oscillation tests to compare tightness and stresses
- Multiple passes of heating, iterative, tedious, precision
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