Structural Systems of the Bollman Truss Bridge at Savage, Maryland

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Structural analysis shows that this Bollman truss behaves in some surprising ways and that the overall design was of high technical quality.

Introduction

The preservation of historic timber, iron, and steel bridges from the eighteenth and nineteenth centuries is increasingly being viewed as an important part of the conservation of the cultural heritage of the United States. Early studies demonstrated that engineering analyses could illuminate the importance of these historic engineering works in ways that more traditional architectural documentation and recording methods cannot accomplish alone.[1] Increasingly, such analyses are being carried out by the Historic American Engineering Record (HAER).[2] This paper describes the results of a field investigation and computerized structural analysis of the Bollman truss bridge in Savage, Maryland (Fig. 1).

The Bollman truss bridge in Savage uses one of the many patented truss designs developed by American engineers during the rapid expansion of the railroads during the mid-nineteenth century. Although widely used on the Baltimore and Ohio Railroad lines, the Bollman truss bridge at Savage is the only remaining example of its kind. The bridge is believed to have been constructed at the Mount Clare shops of the B&O in Baltimore in 1869. It was briefly in main-line service until 1887, when it was moved to its current location, where, located on a spur line, the bridge was no longer exposed to the heavy and frequent loads of the main line. The structure was one of many similar bridges designed for the B&O Railroad from approximately 1850 to 1880 by Wendel Bollman (1814–1884). Bollman, one of many prominent truss-bridge designers active during the middle to late nineteenth century, was born in Baltimore, and, with only a grade-school-level formal education, rose to a high post in the engineering division of the railroad.

Fig. 1 Bollman truss bridge now located at Savage, Maryland. All photographs by Liakos Ariston.

While extensive study has been conducted on both the engineering life of Wendel Bollman and the Savage bridge in particular, including a restoration of the structure, previous engineering analysis has focused on the statically determinate behavior that Bollman is widely assumed to have considered in his design.[3] A structure is considered statically determinate if the forces throughout the structure under a given set of loads can be found using only equations of equilibrium — in other words, by using Newton's third law, which states that for every action there is an equal and opposite reaction. An indeterminate truss contains additional, or redundant, members that increase the overall safety of the structure but render equilibrium an insufficient tool for analysis. The analysis of indeterminate trusses requires significantly more math-

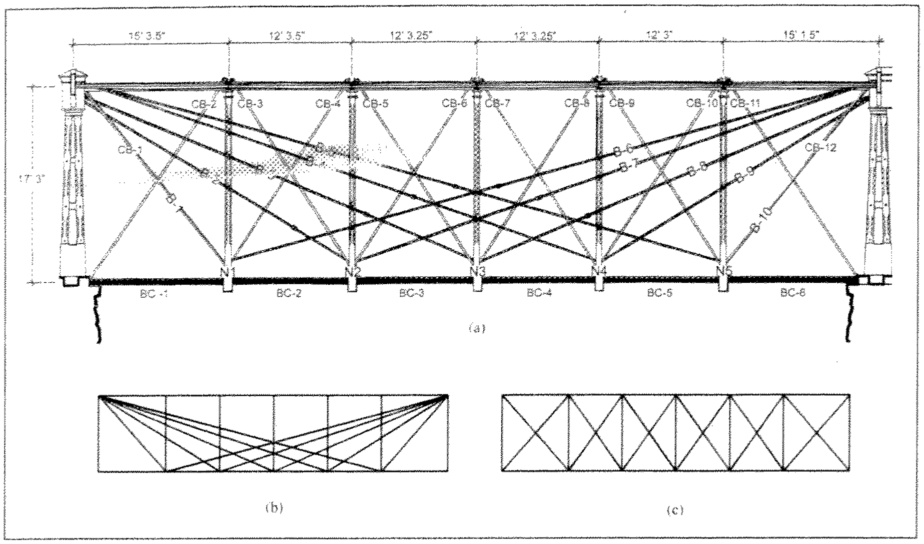

Fig. 2 (a) General bridge elevation showing dimensions and element and node numbering scheme. Modified from a drawing in Brezenski and Jenkins, 1970; (b) the Bollman system of diagonal tension members; (c) the counter-bracing system of diagonals. General elevation drawn from the HAER collection.

ematical sophistication than that of determinate structures.

The assumptions about Bollman's design calculations are supported by the current understanding of the state of technical knowledge at the time of the bridge's construction. Though methods for analyzing indeterminate trusses had just become available at that time, they had not yet been developed in 1850, when Bollman was awarded his patent for the truss.[4] Furthermore, indeterminate-analysis methods were not widely applied in the U.S. when the Savage bridge was built. The only analytical tools available to Bollman were those that could be applied to statically determinate systems.

Field investigation of the connection details of the Savage bridge reveals that the lower chord members function in a surprising way, bearing only compressive loads, and that the members of the secondary, counter-bracing system had the ability to receive pre-load forces, a system that has been shown effective in earlier timber bridges.[5] Structural analysis shows that, while the lower chord members may have been intended partially to resist the longitudinal forces of locomotive acceleration and braking, they also play a significant and previously unknown role in the response of the truss to dead and live gravity loads. The structural analyses also show that the system of counter braces could not have functioned as a part of the primary load-carrying system but must act only as a secondary system providing redundancy and an increased safety margin to the otherwise statically determinate truss system. This system contrasts, for example, with the behavior of the Burr arch-truss system, in which separate structural systems carry the dead and live gravity loads.[6] While a previous restoration, executed in the early 1980s, has returned the Bollman truss bridge to good condition, the results presented here may be useful to future preservation efforts. More importantly, the analysis shown here places Bollman and his design in the context of both historic and modern engineering technology.

General Bridge Characteristics and Idealization

The Bollman bridge at Savage consists of two nominally identical spans consisting of six panels each. The Bollman trusses are placed above the rail bed, forming a through-truss bridge (Fig. 2). The Bollman members illustrated in Figure 2 are labeled B1-B10; the counter bracing members, CB1-CB10; and the bottom chord members, BC1-BC6. The only labeled nodes are those along the bottom chord, as displacements were reported only at these locations. In the end panels, which span approximately 15 feet (4.5 m), Bollman members B1 and B10 run parallel to counter-bracing members CB1 and CB12, respectively. The interior panels, each of which is approximately 12 feet (3.6 m) in span, contain structurally distinct counter-bracing members. Since it is impractical to consider every detail of a structure in an analysis, engineers use idealization to make such analysis possible. Structural idealization is the process, based on engineering judgment, of making simplifying assumptions about a structure's geometry, materials, and loads, ignoring details that are not expected to play a significant role in determining the behavior of the structure.

Member-section properties were based on previously reported values and new field measurements and were used in developing the computer model used in this structural analysis.[7] A previously unreported retrofit to the structure replaced, at an unknown time, the lower chord members in the end panels with members of slightly smaller cross section (Fig. 3). The replacement members are pieces of railroad rail, suggesting that this may have been an emergency repair. This retrofit is not considered in the idealization so as to most accurately reflect the configuration of the structure as it was designed and built.

The Savage bridge is constructed of wrought and cast iron. The vertical and top chord members are cast iron, and all other members are wrought iron. The

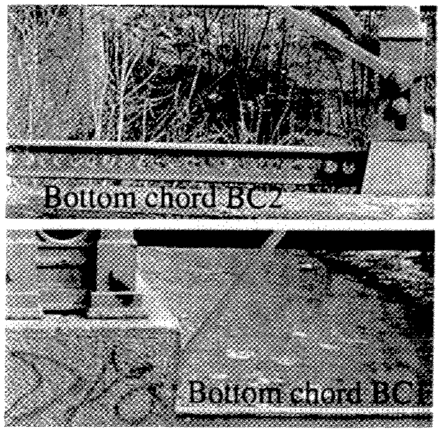

Fig. 3. Lower chord replacement. In the end panels, the original lower chord member (BC2 in image) with circular cutouts (upper frame), has been replaced by a piece of cut railroad rail (BC1 in image, lower frame). This replacement has been made in all eight end panels of the four trusses composing the two spans at Savage.

distribution of materials throughout the structure was determined by observation of member cross-sectional shapes, historical context (which points to the use of wrought iron in tension members and cast iron in compression members at the time of the bridge's construction), and a small number of material tests.[8]

The dead weight of the entire structure (two trusses, flooring system, and trackage) is estimated to be 72 kips (320 KN) (a kip is an engineering unit equal to one thousand pounds, and a kilonewton (KN) is a metric unit of force equal to one thousand newtons. A kilonewton is approximately 225 pounds), resulting in a uniformly distributed dead load of 0.9 kips per foot and equivalent point loads of 6 kips (26.7 KN) per lower panel point, assuming uniform distribution of this load among the panel points. The uniform live load corresponding to the weight of a train typical of the late-nineteenth century, distributed over the entire span, is 3.8 kips per foot or 25 kips (111 KN) per lower panel point. A worst-case live load of 50 kips (222 KN) per panel point was used to model the localized weight of the driving wheels of a typical early-twentieth-century locomotive.[9] The panel-point loads described above represent half of the total load acting on the structure, since the model used in this analysis represents only one of the pair of parallel trusses.

Four observations of bridge details are important to the analysis presented here, the first three of which, to the authors' knowledge, have not previously been reported:

1. The supports approximate a pinned condition.
2. Lower chord connections can transmit only compressive loads.
3. Bracing members have threaded ends and bolted connections, which may have allowed for pre-tensioning of the structure.
4. Bracing and Bollman members are incapable of transmitting significant compressive loads due to their slenderness.

Field investigation showed that the Bollman spans at Savage, which are supported at the lower panel points of the end panels, have pinned or fixed connections. Figure 4 illustrates a typical support condition. In the upper right of the image is the base of the end post, which sits on a masonry pier. In the center of the photograph is the connection of the counter brace and lower chord members (CB2 and BC1, for example), where they are framed into the pier. The end post is supported separately from the bottom chord pair. The key observation is that the foundation is able to provide horizontal and vertical, though not moment, reactions to the counter braces and lower chord members, as well as vertical, horizontal, and at least some rotational restraint to the vertical end posts. A moment, in engineering usage, is a force that induces rotation. An example of moment is the force applied to a wrench to tighten a bolt. A connection or support that does not transmit moment or provide moment reaction is a hinge.

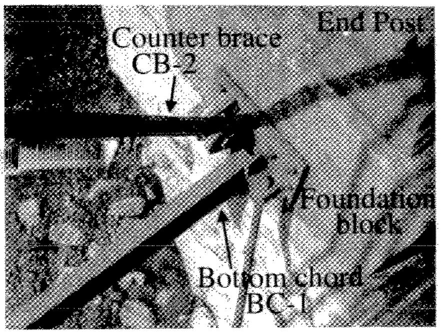

Fig. 4. Support conditions. Though the end post (upper right corner) and counter/lower-chord pair are separately fixed to the pier, each can receive horizontal and vertical reactions. No moment reactions are possible.

The detail of the connection of the lower chord member to the foundation shown in Figure 4 is typical of all connections between lower chord members and vertical posts, as at location N1 for example (Fig. 5). The connection detail is a slotted butt joint in which the lower chord is supported by a U-shaped cradle and bears directly against the transverse floor beam that is framed into the vertical post. No bolts, rivets, or welds are provided, so there is no possibility of transmitting tensile forces through such a connection, since the lower chord member could simply pull out of the connection.

The counter braces have threaded upper ends that pass through the upper chord and are fixed in place by bolts above the upper chord. It would have been possible, during original construction, to apply pre-tension forces to the bracing members through appropriate tightening of the fixing bolt. Though there is no historical evidence for construction using this procedure, it is a reasonable conjecture that this connection detail was at least used to remove slack from the counters, if not to pre-tension the members. This pre-tension force has the potential, as discussed later, to significantly affect the structural behavior of the bridge, as the braces and Bollman members are all so slender that they would buckle under small compressive loads, rendering them unable to transmit significant compressive forces.

The Bollman bridge at Savage was idealized for structural analysis as a truss with pinned connections at the intersection of member centerlines. Only one span of the structure was analyzed, and three-dimensional effects were neglected so that a two-dimensional analysis of one plane truss could be performed. A single pin support was assumed at the intersection of the lines extended from each end post and lower chord. This is an idealization of the actual support condition shown in Figure 4.

In a reference analysis of the structure, linear elastic behavior is assumed. This means that no damage to the structure occurs; no material yields; and the displacements are small compared to the overall bridge dimensions. In the other analyses presented, the diagonal members are assumed to be capable of transmitting only tensile forces, and the lower chord members are assumed to transmit only compressive forces.

Behavior under Uniform Load

A series of analyses demonstrate quantitatively the secondary character of the counter-bracing system and the importance of the lower chord in resisting gravity loads in addition to longitudinal loads. In all cases in this section the uniform dead load of 6 kips (27 KN) per panel point and uniform live load of 25 kips (111 KN) per panel point are used.

Reference configuration. The reference configuration consists of all members of the truss and uniform dead and live load corresponding to 31 kips (138 KN) at each lower panel point of the half truss analyzed in this study. It is assumed, to establish a baseline behavior, that all members can carry tensile and compressive loads without buckling or failure of connections.

The mid-span deflection of the bridge, measured at node N3, is 0.29 inches (7.4 mm). All deflections reported here are downward unless otherwise noted. The axial-force diagram of Figure 6 shows the large compressive force in the upper chord (80–114 kips); the uneven load distribution among the Bollman members is indicated by the varying line weights, tension forces in the lower chord, and the expected alternating pattern of tension and compression in the bracing members. The stresses in the Bollman members are highly nonuniform, ranging from a maximum of 7.29 kips per square inch (ksi) or 50.2 MPa (megapascals, a metric unit of pressure) to a minimum of 0.26 ksi (1.9 MPa). The engineering definition of stress is used here, namely the total force carried by the member divided by the cross-sectional area. This behavior is inefficient because of the variable stresses in the Bollman members. This means that some of the material in the structure is operating near its limiting stress, an efficient utilization of material, and some of the material is operating at far below its limiting stress, meaning that material possibly could be removed in those areas without compromising structural safety. An engineer of Bollman's abilities would not have designed such an inefficient structure. We therefore concluded that he understood that this was not the structural behavior of his system.

Alternating counter braces were found to be in compression. Due to their slenderness, these members are capable of carrying only negligible compressive forces before the onset of buckling, so this result is not realistic. The lower chord members were found to be in tension except in the end panels, which is also not realistic behavior due to the lower chord connection detail.

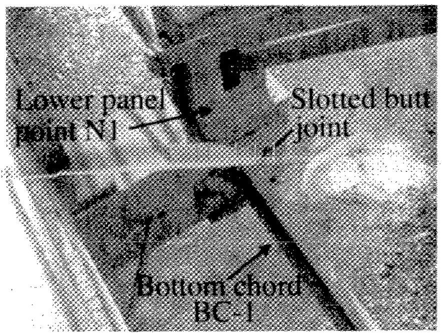

Fig. 5. Lower chord to vertical connection detail. The U-shaped, slotted butt joint is capable of transmitting only compressive forces due to lack of bolts, rivets, or welds at interface of BC1 and N1.

Interaction of Bollman and bracing systems. In order to isolate the interaction between the Bollman and counter-bracing systems, the lower chord members are omitted from this set of analyses, and the Bollman members and counter braces are assumed able to carry only tensile forces. Three configurations of the structure are analyzed in this section; top chord, verticals, and Bollman members; top chord, verticals, and counter braces; and the combined system consisting of all members except the lower chord.

The purpose of this set of analyses is to determine, under uniform load, how the counter-bracing and Bollman systems act together and independently to resist loads placed on the structure. It is a common assumption that the design of Bollman trusses was made based first on the statically determinate Bollman members, with the counter bracing added to provide redundancy to the structure and to distribute concentrated live loads among the Bollman members. These analyses support this hypothesis, as the bracing system cannot carry a significant portion of the load but can aid significantly in improving the safety of the structure.

When the counter braces are neglected, the forces developed in the Bollman members are largest in the members that support the center post (B3, B8) and smallest in the short members supporting the first interior posts (B1, B6, B5, B10); force in the upper chord is constant, which is itself an unusual behavior for a truss. The variation in Bollman-element forces is from a minimum force of 23 kips (102 KN) to a maximum force of 40 kips (178 KN), meaning that the members carrying the least force carry only 42 percent of the force in the members carrying the most force. These results, though here presented as the output of a computerized structural analysis, could easily have been obtained using hand analysis methods available to Bollman at the time of the design of the bridge. The premise that the Bollman members were sized based on the results of such a hand analysis of this statically determinate system is supported by the calculated member stresses, which show nearly uniform stress in the Bollman members, ranging from 7.8 ksi (35 MPa) to 8.6 ksi (38 MPa), only a 9 percent variation from the maximum. A design resulting in uniform stress in the Bollman members would have been very efficient and would have been a desirable objective of Bollman's design process. The calculated stresses result in a factor of safety of more than 3 for the wrought-iron material of the Bollman members and counter braces, which has a yield stress of approximately 30 ksi (207 MPa). The mid-span deflection of this configuration is 0.54 inches (14 mm), or 85 percent greater than in the reference configuration, but still well within serviceability requirements for railroad bridges of the time. This deflection could have been calculated by Bollman at the time of design and would have assured him that the main structural system of the bridge, the Bollman diagonal members, provided sufficient stiffness so that the bridge would not deflect excessively. As Bollman added the counter braces and lower chord to the design he could be assured that not only would these members increase the redundancy of the structure, but they would further increase the stiffness, thereby reducing deflections.

The system of counter bracing, combined with the top chord and the vertical posts, is incapable of supporting a load independently of the system of Bollman members. Such a configuration results in a deflection at mid-span of 8.9 inches (226 mm) and in stresses in the counter braces of 90 ksi (620 MPa). These values exceed both safety and serviceability requirements for the performance of the bridge, and it can be concluded that the bracing system was intended to act as a secondary system in support of the Bollman members, which

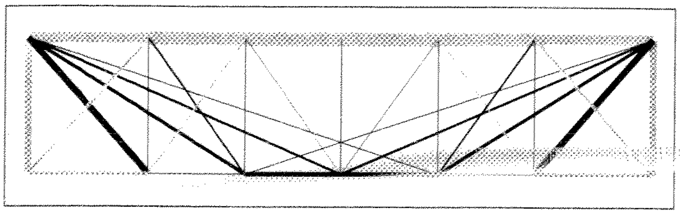

Fig. 6. Axial-force diagram for baseline study showing uneven load distribution in the Bollman members, compressive forces in counter braces (gray), and tensile forces in lower chord (black). Line width is proportional to axial force magnitude (proportionality scale is maintained for all figures unless otherwise noted). Note that the axial force magnitude is not equivalent to axial stress magnitude due to variable member cross sections. All diagrams by the authors.

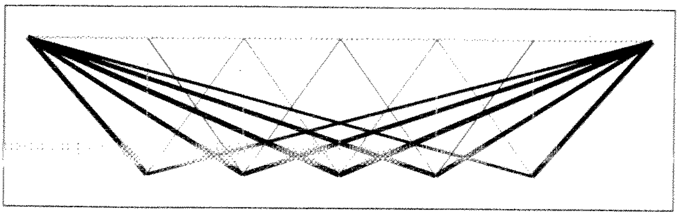

Fig. 7. Axial-force diagram for combined system in the absence of the lower chord. The counter braces, while not measurably increasing the stiffness of the bridge, do redistribute forces in the Bollman members.

were designed to serve the primary load-carrying task. This behavior is opposed to that found, for example, in Burr arch-truss timber bridges, in which the counter-braced truss is an integral part of the primary system for carrying live loads on only part of the span.[10] Nevertheless, the addition of the counter braces provides a significant increase in the safety of the Savage bridge, and their inclusion was a critical factor in the success of the design.

In analyzing the combined system implemented at the Savage bridge, it was found that while the counter bracing does not have a measurable contribution to the bridge stiffness, it does result in a marked redistribution of forces in the bridge members. Referring to Figure 7, the forces in the Bollman members are not uniform when the counter braces are included. Furthermore, while the maximum stress in members B5 and B6 remains nearly unchanged, the minimum stress is reduced by 27 percent from 7.8 kips (35 KN) to 5.7 kips (25 KN). A distinct pattern arises in the stresses of the Bollman members in which the members connecting to posts near the center of the span are more highly stressed than those connecting to posts near the ends of the span. Stresses in the counter braces are found to vary from 2.1 kips (9.3 KN) to 5.7 kips (25 KN), both of which provide an acceptable factor of safety for the design. The mid-span deflection for the combined system is 0.54 inches (14 mm), showing that the presence of the counter braces does not reduce the deflection of the bridge but does result in a redistribution of forces in the structure. For the uniform live-load case the most important function of the counter braces is to provide a redundant load path for the bridge in the case of failure of a Bollman member. While the counter braces do result in a redistribution of forces in the bridge, the overall design, based on Bollman's probable hand calculations of the determinate Bollman system, is still efficient. This combination of systems is an example of how Bollman combined mathematical analysis with practical experience to achieve both a safe and efficient system.

Structural effect of bottom chord members. The purpose of this analysis was to investigate the effect of the bottom chord members on the behavior of the bridge structural system. In the previous section the bottom chord members were neglected in an effort to isolate the relative stiffness and behavioral contributions of the Bollman and counter-bracing systems, and it was found that the bridge can carry gravity loads with an adequate safety factor without the lower chord members. The lower chord members are capable of carrying only compressive forces due to the nature of their connection to the vertical posts and abutments.

Figure 8 shows the axial-force diagram for this condition, in which it is seen that the lower chord members of the end panels and first interior panels are activated in compression, while the lower chord members of the center panels do not experience compression and therefore are excluded from the analysis since their connections cannot transmit tensile forces. Members CB2, CB4, CB6, CB7, CB9, and CB11 go slack in compression while all other braces are in tension, carrying relatively low forces (Fig. 2). Another notable feature of the behavior is the nearly constant axial force in the top chord. For a typical simply supported truss, the axial force in the chords is expected to increase near the mid-span, where bending moment is highest (Fig. 6). This analysis indicates that the constant cross section of the upper chord was indeed an appropriate design for this structural system and that Bollman understood that his design did not result in classic truss behavior.

The presence of the bottom chord completely changes the pattern of stresses in the Bollman members. The members with the greatest stress are now the members nearest to the supports (B1, B12), as opposed to those supporting the mid-span post (B3, B8). The bottom chord members result in a significant reduction of load in some of the Bollman members (B5, B6), while at the same time increasing by 7 percent the stress in members B1 and B10. This new maximum axial stress exceeds the maximum calculated when the bottom chord is neglected.

Although the six counter braces become ineffective when the bottom chord is introduced, the structure becomes stiffer with the inclusion of the bottom chord. Deflection at the mid-span is 0.4 inches (10 mm), whereas the deflection in the combined system without the bottom chord is 0.54 inches (14 mm). This decrease is due entirely to the inclusion of the bottom chord and occurs despite the fact that several of the counter braces go slack under this condition.

The inclusion of the compression-only bottom chord members significantly

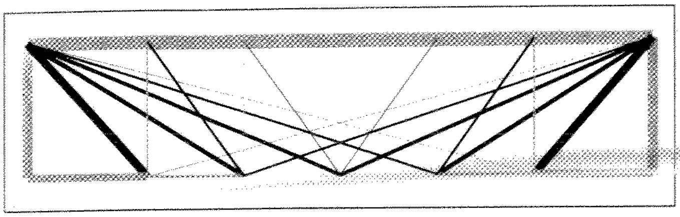

Fig. 8. Axial-force diagram for uniform load case with bottom chord members included and nonlinear analysis accounting for capacity of counters to only carry tension and lower chord members to only carry compression. Bottom chord members are activated in compression in the end panels only, and certain bracing members are assumed to go slack in compression. Dashed lines represent zero force elements.

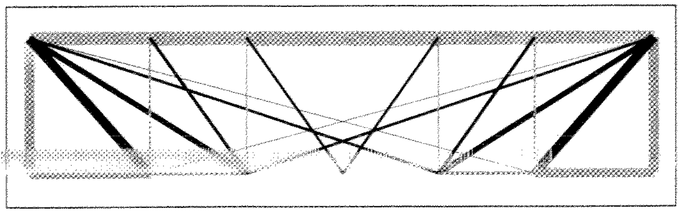

Fig. 9. Axial-force diagram for case of simulated failure of middle Bollman members B3 and B8.

alters the behavior of the end panels of the truss. Concentrating on the left end panel, members B1 and CB1 carry significantly larger loads when the bottom chord is present.

The approach used in sizing the members of the original design, which sought uniform stresses in the Bollman members under uniform load and assumed that the Bollman members act independently of one another and of the bracing and bottom chord, created a structure that has survived for over a century. Modern analysis tools illustrate, however, exactly how the addition of static indeterminacy in the form of the counter braces and bottom chord members complicates the behavior, although the analyses also show that Bollman's assumptions, when coupled with reasonable safety factors, resulted in a safe and efficient design. It should be noted that elastic deformation or settlement of the supports could significantly alter the behavior described in this section. While neither of these effects have been explicitly considered, they could be important for this structure, especially considering that the bridge has been moved from its original location.

The fact that the only bottom chord members carrying large compression are those in the end panels provides insight into one of the field observations. The truss at Savage appears to have undergone retrofits on the bottom chord members in the end panels. The bottom chord at these locations has been replaced with a railroad rail (Fig. 3). The compressive load carried by members BC1 and BC6 is 39 kips in the analysis of the complete nonlinear structural system. Measurements of the cross section of the original and retrofit members give weak axis moment of inertia of 2.23 inches^4 (928,000 mm^4) and 2.63 inches^4 (1,094,000 mm^4), respectively. The moment of inertia is a measure of the resistance to bending of a cross section. Assuming pin connections, the Euler buckling formula, $P_{cr} = \pi^2 EI / L^2$ with E = 28,000 ksi (193 GPa) and L = 183 inches (4,661 mm), gives a buckling load of 18 kips (80 KN) and 21 kips (93 KN) for the original and retrofit members, respectively. The analysis suggests that these members are subject to possible buckling failure. Such failure could explain why only members BC1 and BC6 have been replaced.

Structural redundancy. Analyses show that the Bollman members function as the main load-carrying system of the bridge. The counter braces carry a much smaller proportion of the load and function almost solely to provide additional safety through redundancy in the case of failure of one of the main Bollman members.

In order to quantify the ability of the counter braces to preserve structural safety, members B3 and B8 were removed from the computer model of the bridge to simulate failure of these two members. Analysis of the bridge under this condition, subject to uniform live and dead loads, yields a maximum displacement at node N3 of 0.53 inches (13 mm), which, while significantly larger than the displacement of 0.40 inches (10 mm) found for the intact structure, is still well within serviceability requirements. The axial-force diagram in Figure 9 shows a noticeable increase in the force in the center-panel counter braces as these members act to redistribute the load originally carried by members B3 and B8. The increase in force in these members (CB5 and CB8) is from 5.8 kips (26 KN) and 5.9 kips (26 KN), respectively, to 19 kips (85 KN) in each, an increase of over 300 percent. Despite this large increase in force, the stresses in these members, now found to be 8.2 ksi (56 MPa), are still within allowable limits, and the bridge is found to be able to sustain such severe failure without collapse. The remaining Bollman members also see an increase in axial force when the members and B8 are assumed to have failed. For example, the axial force in B9 increases from 32 kips (142 KN) to 39 kips (174 KN), which nonetheless still results in a stress of less than 10 ksi (69 MPa). Further simulation indicates that the bridge is able to withstand failure of up to six of the main Bollman members without collapse, though immediate rehabilitation of the structure would be required.

Behavior under Nonuniform Load

Understanding the response of railroad bridges to nonuniform loads is more important than for highway or pedestrian bridges since the live load, comprising the train, is much larger than the dead load, or weight of the bridge. Nonuniform loads are present on long-span railroad bridges when a train is located only partially on the span of the bridge. Nonuniform loads arise for short-span bridges when, for example, the driving wheels of a locomotive, which carry a large percentage of the locomotive weight, are present on the bridge. The nonuniform load modeled here consists of a single-point live load of 50 kips (222 KN) applied at a panel point and superimposed on the dead load of 6 kips per panel point. The single-point load is representative of the portion of the weight of a large locomotive that is supported on the driving wheels and is assumed, in the worst case, to be centered over a lower panel point. Three loading scenarios are considered in which the point load is applied at N1, N2, and N3, which can be thought of as representing the movement of a locomotive across the span.

The most notable feature of the bridge behavior under nonuniform load is the increased engagement of the bottom chord members. Figure 10 shows the axial force diagrams for each of the three moving-load cases, corresponding to maximum deflections of between 0.2 inches and 0.3 inches. For nonuniform load cases the center-panel bottom chord members can experience compressive forces, albeit of small magnitude. This situation contrasts with the uniform load-case results, in which center-panel bottom chord members never experience compressive forces and therefore do not function structurally (Fig. 8). This result is significant because it shows that, despite the fact that the lower chord can transmit only compressive forces, the lower chord members do function structurally in all panels of the bridge under certain load scenarios.

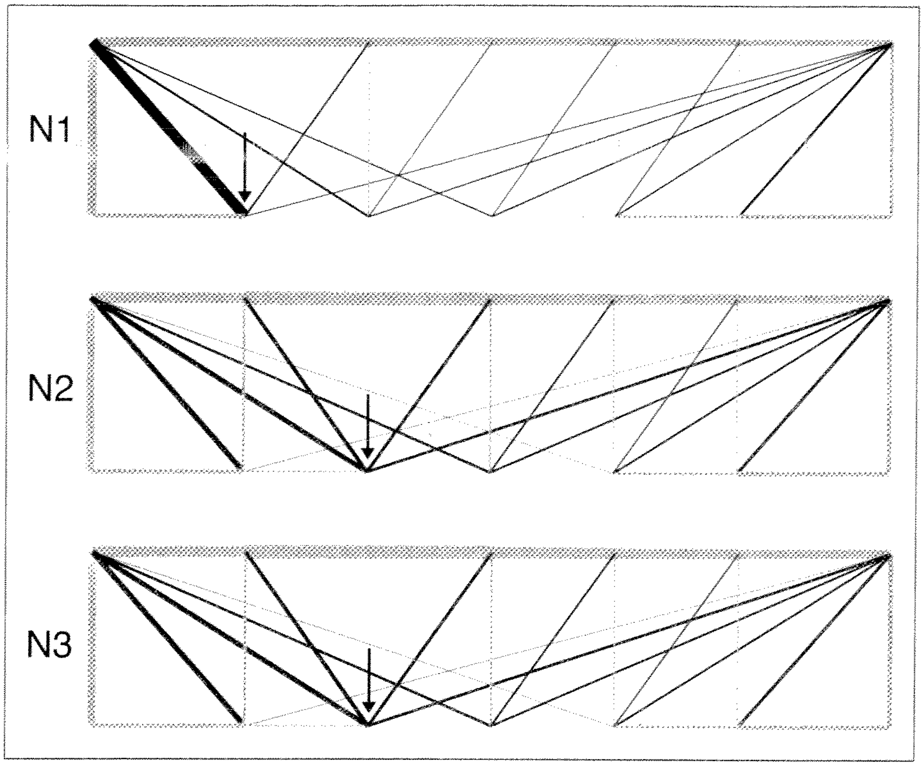

Fig. 10. Axial-force diagrams for moving load case and nonlinear analysis method. For nonuniform loads the lower chord, which is capable of transmitting only compression due to its connection detailing, is engaged over a greater portion of the bridge span than for uniform load cases (see Fig. 8). When member nonlinearity is considered, verticals at the point of application of the concentrated load become zero force members.

Pre-tensioning of Counter Braces

One of the main observations of the previous analyses presented in this paper is that a large number of the counter-bracing members are structurally inactive due to their extreme slenderness and are thus unable to carry compressive loads. Field investigations revealed that the connections of the counter braces would have allowed the members to be pre-tensioned by the simple tightening of a bolt at the member end. Such pre-tensioning could make the braces structurally effective over a much broader range of loading conditions. While there is no direct evidence that such tensioning was applied to the counter braces, the following analysis shows that the structural behavior of the bridge is measurably improved by such tensioning. The analysis is not included to imply that Bollman intended this as part of his design.

As a preliminary investigation of the possibility of pre-stressing of the braces, a pre-stress of 4.3 ksi (30 MPa) is introduced to all of the bracing members in the analysis model. Again, there is no evidence that pre-tensioning was applied to this structure, yet the connection details would allow for it, and it is known that such forces were introduced in other period bridges.[11] This amount of pre-tension corresponds to an elongation in the interior panel braces of approximately 0.1 inches (2.54 mm), which would have been easily attainable using the bolted connection at the upper chord.

When the uniform dead and live loads are superimposed on the pre-tension forces, members CB6 and CB7 experience net-tensile force and therefore remain structurally effective. If the pre-tension load is increased to 8.6 ksi (60 MPa), a large but still reasonable amount, all counter-bracing members remain in tension under uniform dead and live loads. Imposition of even this relatively large pre-tension force leads to stresses no greater than 15 ksi (103 MPa) anywhere in the bridge but does lead to very uneven force distribution in the counter braces, some carrying nearly zero force and some tensile forces of approximately 30 kips (134 KN). This suggests that selective or differential pre-tensioning of the counters may further improve the performance of the structure. Ongoing studies will seek to further explain the possible effects of counter pre-tension on the behavior of the bridge under various loading scenarios.

Conclusion

The Bollman truss bridge at Savage, Maryland, provides an important link in the history of structural engineering in the United States. The bridge was designed using only hand calculations and engineering judgment; computerized structural analysis provides important insight into the behavior of the complicated structural system. The primary load-carrying system of the bridge is a network of Bollman members supporting the vertical posts. The system of counter braces serves two important purposes: to distribute nonuniform loads to the pairs of Bollman members and to provide redundancy in the case of failure in the statically determinate Bollman system. It is also found that the lower chord members can significantly redistribute forces in the structure, resulting in nonuniform stresses in the Bollman members. The bottom chord functions in compression even under gravity loads, a highly surprising behavior for the bottom chord of a simply supported span.

Statically determinate analysis of the main Bollman members shows that they were correctly sized to obtain nearly uniform axial stresses. Such a design would have been possible in the 1860s using the hand-calculation methods available to Wendel Bollman. Indeterminate and nonlinear analysis shows, however, that the indeterminacy introduced to the structure by the addition of the lower chord and counter-bracing members significantly alters the force and stress distribution in the bridge. While these members serve their purpose of strengthening the bridge and render it less susceptible to collapse, their presence alters the member forces that Bollman would have used in his design. This finding does nothing, however, to detract from the brilliance of Bollman's work. His extensive experience with truss bridges gave him the ability to superimpose the counter-bracing system on the Bollman system to increase safety while maintaining efficiency.

Under nonuniform loads the lower chord is increasingly activated in compression. The introduction of pre-tension forces in the counter braces, which is possible given the connection details, could have significantly stiffened the structure and increased its redundancy.

All of the analyses presented here point to the fact that the end panels behave in a qualitatively different manner than the interior panels. The lower chord is activated under all load cases, and member forces can be significantly larger in the end than the interior panels. The lower chord members in the end panels are susceptible to buckling failure in the out-of-plane direction. This means that the lower chord members would buckle with a deflected shape that breaks the plane of the truss panel of which they are members. This deflection would be parallel to the plane of the deck, that is, horizontal. This finding provides a possible explanation for the replacement of these members in the bridge.

Wendel Bollman, designing in the middle of the nineteenth century, practiced engineering at a time of significant transition, from timber to iron construction and from intuition and field experience to a combination of experiment and mathematical analysis for design. The Bollman truss became the primary short-span bridge of the B&O Railroad, and the specimen at Savage has survived for almost 150 years, a testament to Bollman's skill and creativity as a designer. The analysis presented in this article demonstrates that Bollman's design is safe, serviceable, and efficient, with a suitable factor of safety, reasonably small deflections, and an ability to withstand the failure of individual members.

A question arises, then, as to how Bollman arrived at this design and to what degree his thinking about the design was influenced by the state of technical knowledge when the design was patented in 1850 and the bridge was built in 1869. Bollman lacked formal education beyond the age of 11 and gained his engineering skill through apprenticeships as a carpenter and work for the B&O under the guidance of Benjamin H. Latrobe, the chief engineer.[12] His 1850 patent for the design came only three years after Squire Whipple published his early book on truss analysis.[13] In this work, in D. J. Jourawski's text in 1850, and in Herman Haupt's book in 1851, methods are presented only for analyzing statically determinate trusses, and statically indeterminate trusses are analyzed by use of approximations made according to engineering judgment regarding the structure's behavior.[14] The first exact analysis of indeterminate trusses by Alfred Clebsch in 1862 predates construction of the Savage span but postdates the Bollman patent.[15] At the time of the design leading to the patent, therefore, Bollman would have had available to him the tools to analyze a statically determinate truss, since the construction of the B&O Railroad, perhaps the United States' major engineering endeavor at the time, would almost certainly have provided Bollman access to Whipple's text. Bollman could therefore have used Whipple's techniques to determine the forces in the Bollman members, neglecting the effect of the counter braces and adding the counter braces for redundancy based on his extensive experience. The design of the Savage span, 19 years later than the patent, does not differ significantly from the patent design, implying that Bollman did not consider major changes to the design necessary. Thus, Bollman likely designed based primarily on his experience working with different bridge types during his time with the B&O, supplemented by analysis of the statically determinate subsystem formed by the Bollman members. In the years following 1850, however, he certainly was exposed to steadily more advanced analysis techniques. It is possible that he returned to the design to check its safety both by analysis and experiment.[16] Had he done this, as this article suggests, he would have found that his design, while behaving somewhat differently than he may have initially assumed, was of very high quality and safety. The design to this day stands out as one of the highest quality and one that represents the best of the creative and technical capabilities of nineteenth-century-American structural engineers.

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