Fatigue prone details in steel bridges

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ABSTRACT: This paper reviews the results of a large investigation of more than 100 fatigue damage cases, reported for steel and composite bridges. The damage cases were categorized according to the type of detail in which they were encountered and the mechanisms behind fatigue damage in each category were identified and studied. It was found that more than 90% of all reported damage cases are of the deformation-induced type and are generated by some kind of unintentional or otherwise overlooked interaction between different load-carrying members or systems in the bridge. Poor detailing, with unstiffened gaps and abrupt changes in stiffness at the connections between different members, also contributed to fatigue cracking in most details.

1 INTRODUCTION

In steel bridges, fatigue is often a major problem limiting the load-carrying capacity and the residual life of existing bridges. The correct identification of fatigue-prone details in a bridge, along with well-planned inspection routines and successful strengthening and repair schedules, can contribute to the continuous satisfactory performance of the bridge during its service life. Also in new construction, it is important that structural details which have been shown to be susceptible with reference to fatigue are avoided in design. As a result, information about the fatigue performance of various bridge details in existing bridges is vital for the bridge manager or owner but also as feedback for bridge designers and engineers.

In a recently concluded investigation of the fatigue performance of existing steel and composite bridges (Al-Emrani, 2006), fatigue damage cases which had been reported for various bridge types and details were collected. A total of more than 100 damage cases were studied and categorized according to the type of detail and/or the mechanism behind the observed fatigue cracking. The results of this study show that more than 90% of all reported cases are of the kind caused by secondary effects, so-called deformation-induced cracking. This type of fatigue damage is often the result of secondary restraint forces generated by some kind of unintentional or overlooked interaction between different members in the bridge. Poor detailing, with unstiffened gaps and abrupt changes in stiffness at the connections between different members, also contributed to fatigue cracking in most details. Design codes and evaluation specifications generally provide very little guidance on the way this kind of fatigue damage should be accounted for or prevented. It is the responsibility of the

bridge designer to ensure – through good detailing – that these secondary effects and the kind of fatigue damage associated with them are avoided.
In this paper, a number of common bridge details which have been shown to be susceptible to fatigue damage are reviewed. The mechanisms behind fatigue cracking in each detail type are discussed and issues related to poor detailing and overlooked or unforeseen behavior and load effects are addressed.

2 DETAILS WITH CHANGE IN SECTION

Several types of bridge details exist, in which a change in the cross-section of the element gives rise to a complex state of stress comprising additional stress components which could be high enough to cause fatigue damage in the detail. These stress components are usually somewhat difficult to predict by simple analysis and are sometimes neglected or overlooked by the designer.
A detail in which numerous fatigue problems have been found in the United States and Japan (see for example Miki et al. (2004)) can be found in Gerber bridges and in bridge girders with reduced depth at the supports. According to beam theory, bending stresses in the girder near the support are negligible and the beam is designed in these locations with respect to shear force alone. Owing to the reduction in girder depth and the resulting change in cross-section, the deformation of the girder will induce additional tangential and radial stresses in the girder web and in the flange-to-web welds along the curvature of the out-cut, see Figure 1.
Damage cases involving fatigue cracking in the web of the girder, as well as in the flange-to-web welds, have been reported. In the latter case, the connection between the flange and web was made by means of fillet welds. The cracks in the girder web can grow either in a direction tangential to the flange curvature (caused by the radial stress component) or in a radial direction (generated by the tangential stress component), see Figure 1.

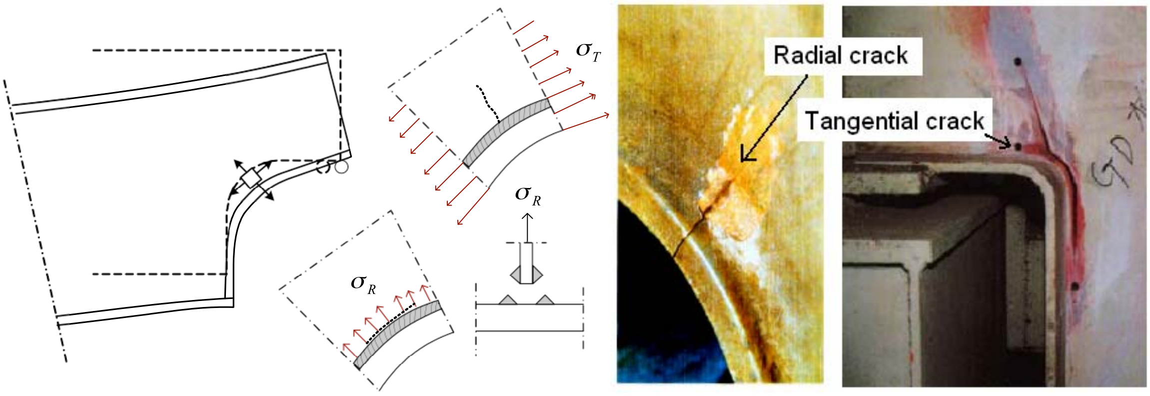

Figure 1. Tangential and radial stresses in beams with reduced depth and the three cracking modes that can be obtained in this detail and examples of radial and tangential cracks.

3 VIBRATION-INDUCED FATIGUE CRACKING IN BRIDGE HANGERS

Vertical hangers in steel arch bridges are usually only designed to take account of the axial forces they carry. Details of the hanger connections to the arch and to the bridge deck are generally designed to ensure a moment-free connection. For this reason, the hangers are often assumed to be pin-connected at both ends.
Several cases have been reported in which fatigue cracking at the connections of bridge hangers were observed; see for example Fisher (1984) and Åkesson (1991). In most cases, a combination of two different mechanisms has contributed to fatigue cracking in these details.

- *Vibration*: The slender hangers usually have very low bending stiffness, which makes them very sensitive to resonance. The cables can be excited by traffic loads on the bridge and/or wind loads.

- *Secondary stresses due to connection stiffness*: Ideal moment-free pin connections do not exist in reality! Even when designed as such, a connection will always acquire some rotational stiffness inherent to detailing or gradually during the service life of the bridge, due to corrosion, for example (so-called freezing).

Oscillation of the cables combined with overlooked or unforeseen connection stiffness might result in numerous cycles with a fluctuation in moment (bending stresses) in the hanger near its connections. Even if the magnitude of these bending stresses might be relatively low, the large number of loading cycles caused by vibration may result in fatigue cracking in the detail.

Figure 2 shows an example of an arch bridge in which the hangers have developed fatigue cracking at their connections to the steel arch. This railway bridge, which was built in 1943, has a span of 61 m and comprises a steel arch with two ties (stiffening girders) connected by floor beams. The hangers were made of steel cables with a diameter of 79 mm. A detail of the hanger connection to the steel arch is also shown in Figure 2. The fatigue damage was detected in the early 1980s; some hangers had cracked and had totally separated from their connections to the arch. The cracking which took place at the threaded part of the hanger was attributed to a combination of oscillation and secondary bending of the hangers at their connection to the steel arch.

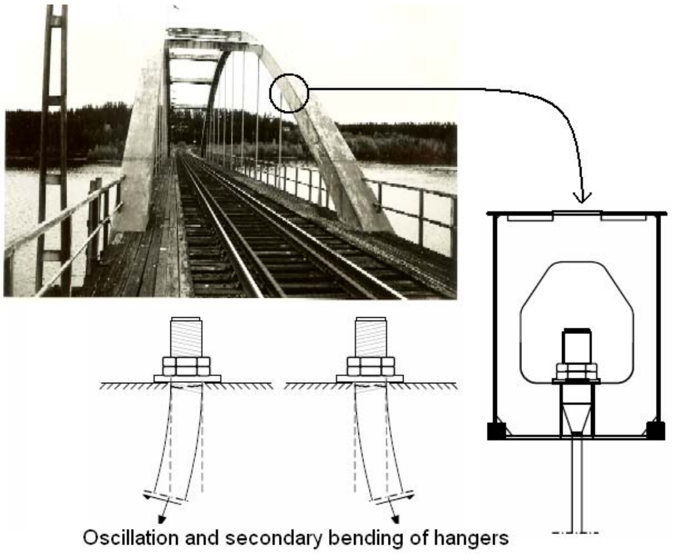

Figure 2. Fatigue cracking of the hangers in the bridge over Skellefte River in Sweden.

4 BRIDGE GIRDERS AND STRINGERS AT TIMBER TIE CONNECTIONS

In many old railway bridges, traffic loads on the bridge are transferred to the longitudinal load-carrying members (bridge girders or stringers) via timber ties resting on these members and connected to them by means of hooks or bolts. Several fatigue damage cases in which the stringers exhibited fatigue cracking at locations beneath the timber ties have been reported; Horikawa et al. (2004), Sweeney (1978). In welded girders, the cracks often grow along the toe of the welds connecting the girder web to the upper flange. In older riveted girders, the cracks were found along the fillet of one of the L-profiles forming the upper flange of the girder, see Figure 3.

There are two principal actions that may contribute to the initiation of this kind of fatigue cracking.

1. *Bending deformation of the timber ties under the action of vertical axle loads*. The corresponding rotation of the ends of the timber tie forces local bending of the girder flange to which the tie is connected, along with an out-of-plane deformation of the girder web.
2. *Transverse forces on the bridge, causing the out-of-plane bending of the girder web*. This effect is more pronounced in curved bridges, but it can also be induced by different track irregularities in straight bridges.

Both actions have a very short influence line, giving rise to a large number of loading cycles every time a train passes.

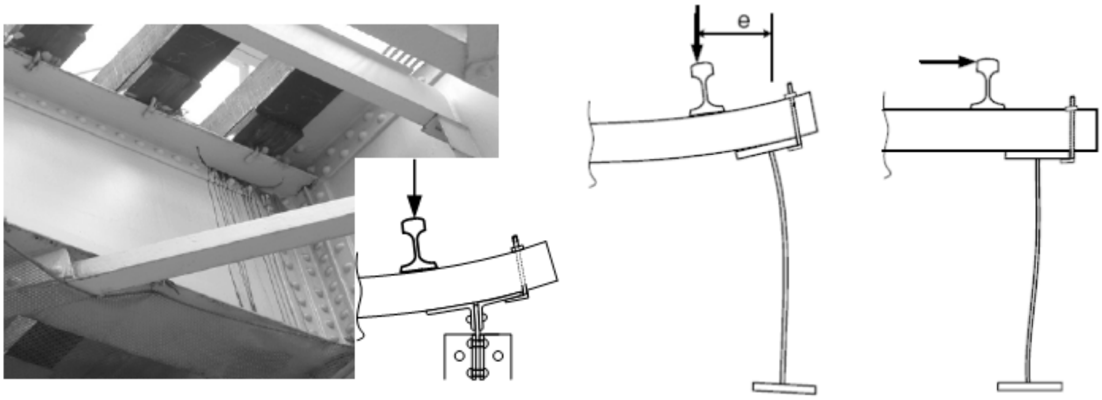

Figure 3. Example of fatigue cracking in stringers at timber tie connections and the deformations inducing this cracking.

Fatigue damage due to the interaction between bridge girders and timber ties can be mainly found in locations along the girder, where the deformation resulting from this interaction is locally concentrated in flexible areas (i.e. where more global deformation like that illustrated in Figure 3 is restrained). These locations are, for example, found near the connections of the stringers to the floor beams or near diaphragms and cross-bracings, owing to the higher restraining effect at these locations. The concentration of deformation to very small areas in the girder web or to the outstanding leg of the girder flange in riveted stringers results in high bending stresses at these locations and leads gradually to fatigue cracking. The same mechanisms have resulted in similar fatigue cracking in highway bridges. The deformation in these cases was induced by the transverse bending of the concrete deck which acts compositely with the steel girders.

5. DIAPHRAGMS AND CROSS-BRACING CONNECTIONS

Diaphragms and cross-bracings are vital elements which are used in many bridge types to ensure the lateral stability of the bridge during construction and/or against lateral and torsional loads acting on the bridge. In many cases, these stabilizing elements are connected to the longitudinal members of the bridge (main girders or stringers) through connection plates, which are welded, bolted or riveted to the girder web. In welded bridges, the common practice for many years has been to omit the welds connecting the vertical stiffeners to the girder flange in order to avoid a detail with low fatigue strength. Instead, the connection plate is either cut short a distance from the flange or fitted to the flange, either directly or via a piece of steel.

The detail near the termination of transverse plates (or vertical stiffeners) used to connect diaphragms or the cross-bracing is known to be one of the most critical in terms of fatigue in steel bridges. Fatigue cracking here is primarily found in the girder web, starting at the end of the stiffener and growing almost horizontally in a direction parallel to the normal bending stresses in the web, see Figure 4. This type of fatigue cracking has been reported in both railway and highway bridges and can be found in many bridge types, including two- and multi-girder bridges, box girder bridges and truss bridges. The mechanism behind fatigue cracking at diaphragm and cross-bracing connections is, however, the same, irrespective of bridge type. Loading cases, which result in secondary bending of the bridge girders (in the weak direction) and/or torsional deformation of the bridge cross-section, cause uneven deflection of the girders, which is resisted by the diaphragm or the cross-bracing elements. Consequently, tensile and compressive forces are generated in these elements, acting perpendicular to the plane of the girder web and causing secondary bending stresses which are localized in the unstiffened part of the web between the girder flange and the end of the connection plate, see Figure 4.

In railway bridges, these transverse and torsional loads are more obvious in curved and skewed bridges, but they may also be generated in straight bridges by possible track eccentricities or irregularities. The same effects are clear in highway bridges where the truck load can take any position in the transverse direction of the bridge, causing the uneven deflection of the bridge girders.

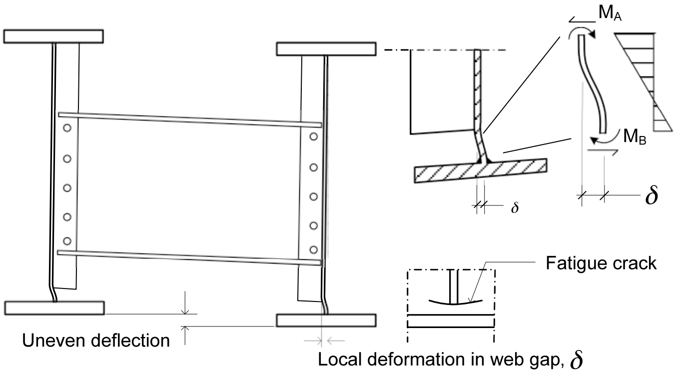

Figure 4 The differential deflection of bridge girders results in high local bending stresses in unstiffened web gaps between the girder flange and the termination of cut-short connection plates.

Furthermore, riveted connections of the type discussed here have also been shown to be prone to fatigue cracking; Yen et al. (1990). In this case, the fatigue damage was found either in the outstanding leg of the connection angle or in the rivets connecting the angle to the girder web, see Figure 5.

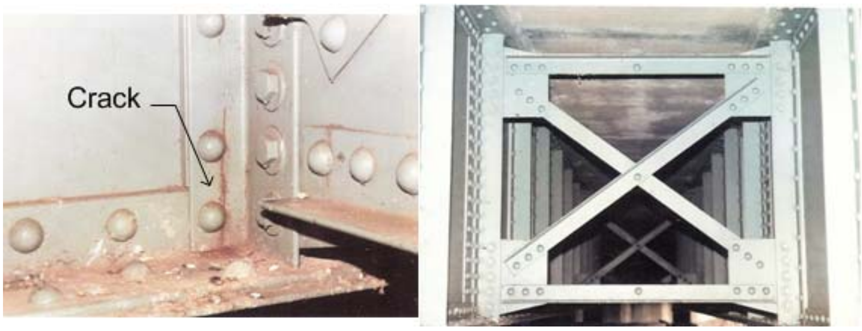

Figure 5 Fatigue cracking in the riveted connection of cross-bracing elements.

6. STRINGER-TO-FLOOR-BEAM CONNECTIONS

In many existing bridges, mechanically fastened stringer-to-floor-beam connections are made using double angles riveted or bolted to the web plates of both members. The common engineering practice has been to design these connections to take account of shear forces alone (their load-carrying function being to transfer the stringer end reactions to the floor beam). While this assumption may be adequate for an ultimate limit state design, the behavior of these connections under moderate loads might differ substantially.

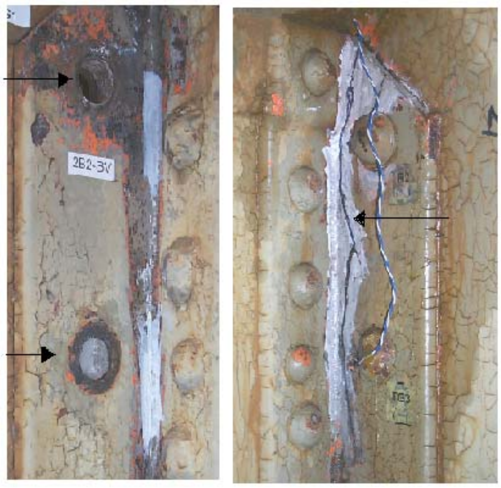

Figure 6. Examples of fatigue damage in riveted stringer-to-floor-beam connections.

Connections of this type have displayed large-scale vulnerability to fatigue cracking. A large number of cases of damage in which fatigue cracks were detected in the connection angles have been reported; Al-Emrani (2002), Al-Emrani et al. (2004). The cracks usually start in the outstanding leg of the connection angle and grow along the fillet of the angle. Figure 6 shows an example of this kind of fatigue cracking. In old riveted connections, rivet failures are also very common. Cracking here starts in the junction between the rivet head and shank (caused by prying and rivet bending) and finally results in the total separation of the rivet head. Fatigue damage of this kind is generally located at the top of the connection, but cases of damage with fatigue cracking and/or rivet failure at the bottom of the connection have also been reported; Al-Emrani (2002).

Fatigue cracking in stringer-to-floor-beam connections is generated by secondary effects which are deformation induced in nature. Two mechanisms can be identified here.

1. *The rotation of stringer ends associated with bending*. Even though double-angle connections were designed as simple shear connections, it is generally inevitable that these connections also acquire some rotation stiffness, thus partially restraining the rotation of stringer ends. Consequently, negative bending moment will develop at the ends of the stringers, subjecting the fasteners and the angles of the connections to load effects which are not taken into account during design, see Figure 7. This kind of action has a relatively short influence line, giving rise to a large number of loading cycles during the service life of the bridge.
2. *An overlooked interaction between the floor system (stringers and floor beams) and the main load-carrying structure (main girders or main trusses, for example)*. Bending deformation of the main truss bridge, for instance, involves the longitudinal displacement of the truss joints to which the floor beams are connected. The floor beams are, however, partially restrained from following this deformation due to the axial stiffness of the stringers and their connections to the floor beams. As a result, secondary axial forces will develop in the stringers and their connections to the floor beams, while the latter will be subjected to secondary bending (in the weak axis), see Figure 8. This kind of interaction has an influence line, which is equal to the span of the bridge and, in the case of railway bridges, there is essentially one loading cycle every time a train passes.

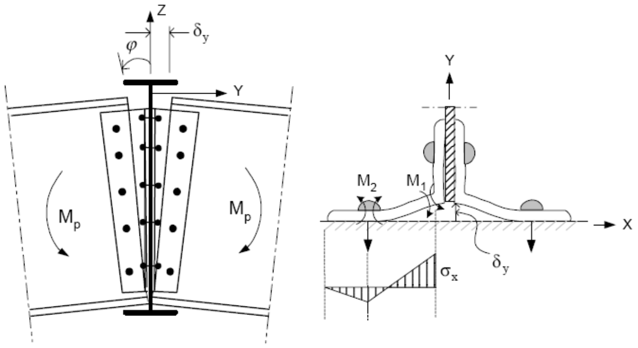

Figure 7. Secondary bending at stringer ends due to restrained end rotation. Bending and axial stresses at the top of the stringer-to-floor-beam connection might be high enough eventually to result in fatigue cracking.

Fatigue cracks in the double angles of stringer-to-floor-beam connections are generated by bending stresses and are therefore somewhat difficult to detect in the early stages, i.e. before the surface crack grows through the thickness of the connection angle. Fatigue tests on bridge parts incorporating riveted double-angle connections show, however, that the propagation rate of these cracks is very low; Al-Emrani (2002). Nor does the presence of these cracks directly threaten the integrity of the load-carrying function of the floor system. However, in one case at least, fatigue cracking in stringer-to-floor-beam connections was reported to result in the total separation of the stringer, a failure mode which might jeopardize the entire performance of the bridge (International Institute of Welding).

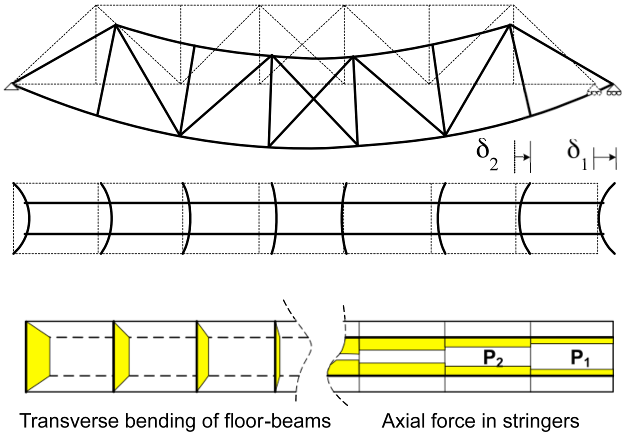

Figure 8. The interaction between the floor system (stringers and floor beams) and the main bridge trusses results in secondary axial forces and bending moment in the stringers and the floor beams respectively.

7 CONNECTIONS BETWEEN FLOOR BEAMS AND THE MAIN LOAD-CARRYING MEMBERS

Like stringer-to-floor-beam connections, the connections between the floor beams and the main load-carrying elements or system (main girder, main trusses, arch ties etc.) have also displayed numerous fatigue problems. In principle, the interaction mechanisms behind fatigue cracking in these two types of connection are the same. Secondary bending moment (in the plane of the floor-beam web) might develop at the ends of floor beams as a result of the rotational restraint provided by their connections to the main load-carrying elements. Furthermore, the interaction between the floor system (stringers and floor beams) and the main load-carrying structure might result in secondary out-of-plane bending of the floor beams, as illustrated in Figure 8 above.

Figures 9 show two examples of fatigue cracking caused by the restrained rotation of floor-beam ends. In mechanically fastened connections, the fatigue damage is generally found in the connection angles or the rivets (or bolts) connecting the angles to the main load-carrying element; International Institute of Welding, Shenton et al. (2003). In welded details, where the floor beam is connected to a welded transverse plate, cracking has been reported in the main girder web (types A and C in Figure 9) or in the connection plate along its fillet weld to the main girder web (type C); International Institute of Welding, Yen et al. (1990), Fisher (1984).

The second type of interaction (transverse bending of the floor beams) has also resulted in fatigue damage in many steel bridge types. One example is shown in Figure 9. In this case, the upper flange of the floor beam is cut short near the floor beam to main truss connection, leaving a small – locally flexible – gap in the floor-beam web where the deformation is concentrated. The same kind of fatigue cracking has been reported for highway girder bridges by Yen et al. (1990), Fisher (1984), in truss bridges, International Institute of Welding, and in arch bridges; Shenton et al. (2003).

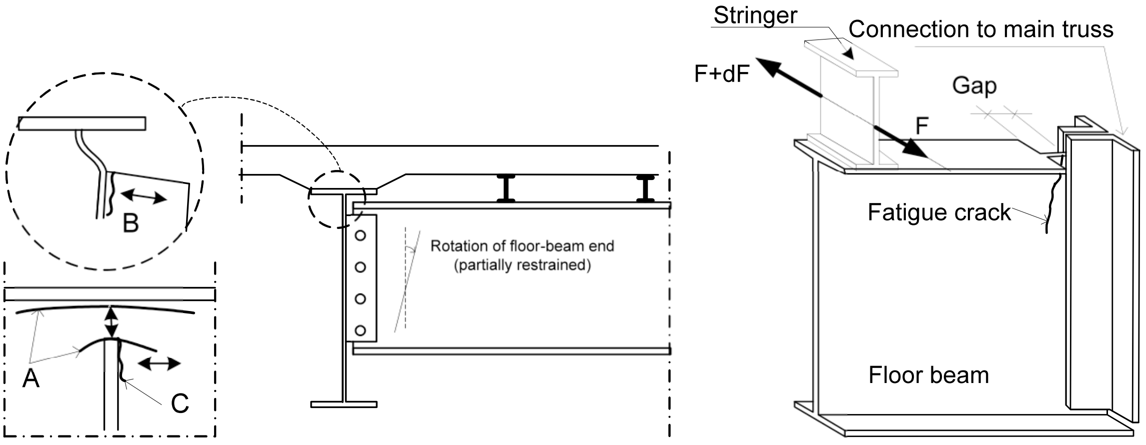

Figure 9. Fatigue cracking by the two different interaction types in floor-beam to main girder connections.

8 SUMMARY AND CONCLUSIONS

A comprehensive investigation of the fatigue performance of steel bridge details reveals that the majority of cases of fatigue damage which have been reported for highway and railway bridges are of the type caused by secondary load effects. In most cases, unforeseen (or otherwise overlooked) interaction between different members and load-carrying systems in the bridge, often combined with poor detailing, have been the cause of fatigue cracking in bridge details. In some cases, a complex stress state may also exist in some structural details. They are frequently difficult to take into account in a simplified design and may also be overlooked by the designer. The basic mechanism behind most types of fatigue cracking caused by secondary effects is an applied deformation, which is repeated cyclically.

A common feature in many details which have experienced this kind of fatigue cracking is that they incorporate some kind of abrupt change in stiffness, typically in unstiffened gaps where the applied deformation is concentrated. This often results in high local stresses which might eventually lead to fatigue cracking in the detail. The most common types of deformation-induced fatigue damage can be found in the connections between stringers and floor beams, between the latter and the main load-carrying elements in the bridge and at the connections of diaphragms and cross-bracings. Moreover, fatigue damage in details in orthotropic decks and in bridge elements with coped ends or cut-short flanges at their connections to other elements is fairly common.

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