XXIV Konferencja Naukowo-Techniczna
Szczecin-Międzyzdroje, 26-29 maja 2009
XXIV awarie budowlane

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FATIGUE CRACKS IN DAPPED STEEL HIGHWAY BRIDGE GIRDERS

RYSY ZMĘCZENIOWE W STALOWYCH DŹWIGARACH MOSTOWYCH O ZMIENNYM PRZEKROJU

Abstract The fatigue behavior of 90-degree, "bent-plate" dapped girder end details is examined analytically using finite element models, and empirically based upon a review of fatigue failures involving the detail in service. In Japan, this detail has been associated with severe fatigue problems in service involving both root and toe cracks in fillet welds connecting the web plate to the bent portion of the flange plate. As they propagate, the cracks generally form branches, some of which propagate around the apex of the bend, and others that are more severe propagate vertically through the web plate. By analysis, two zones of local tensile stress concentration are observed in the web plate where it joins the bent flange plate. At both locations, the maximum principal stress is tensile and nearly perpendicular to the weld joining the web plate to the flange plate.

Streszczenie Zachowanie zmęczeniowe przypodporowej końcówki stalowego dźwigara mostowego o 90 stopniowym wyokrągleniu w podciętej części analizowano za pomocą metody elementów skończonych oraz empirycznie bazując na przeglądzie uszkodzeń wywołanych zmęczeniem w podobnych przypadkach. W Japonii ten fragment mostów spowodował cały szereg problemów zmęczeniowych związanych z pękaniem spoin pachwinowych w grani jak i na krawędzi w miejscu połączenia środnika dźwigara z wygiętą częścią pasa. Rozchodzące się pęknięcia tworzą gałęzie, z których część propaguje wokół wierzchołka zagięcia, a pozostałe, które są o wiele bardziej niebezpieczne, propagują pionowo przez materiał środnika. W wyniku zastosowanej analizy MES zaobserwowano dwie strefy koncentracji lokalnych naprężeń rozciągających w płycie środnika w miejscu, w którym łączy się ona z wygiętym pasem dolnym. W obu tych miejscach maksymalne naprężenia główne są rozciągające i skierowane są prawie prostopadle do spoiny łączącej środnik z pasem.

1. Dapped Plate Girders

Bridges in the state of Texas, USA often comprise long steel girder spans immediately adjacent to shorter prestressed concrete girder spans. In such cases, there is usually a mismatch in member depth where the steel and concrete girders meet end-to-end over a common bent. This geometric problem is commonly resolved in one of two ways. A step is sometimes placed in the bent cap to accept the shallow concrete girder on one side and the deep steel girder on the other (Figure 1a). Alternatively, the deep steel girder can be made shallower at its terminal end, or dapped, to rest at the proper elevation on a flat bent cap end-to-end with the concrete girder (Figure 1b). The dapped alternative (Figure 1b) is the subject of this study. Note that there can be other design situations that call for the use of dapped steel girders in bridge construction projects. For example, architectural program requirements might stipulate the use of a dapped girder end detail.

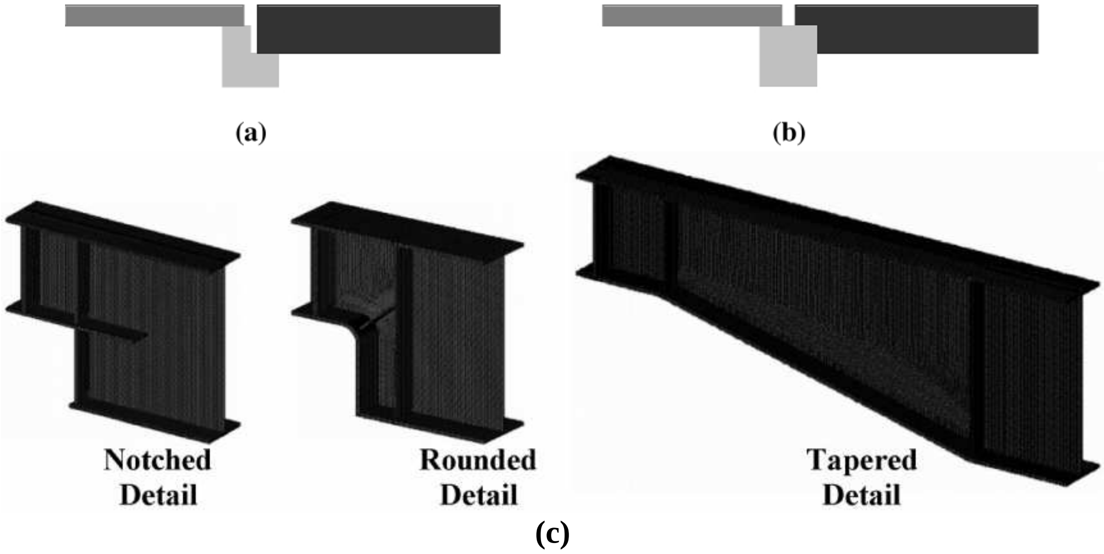

Figure 1. (a) Stepped Bent Cap. (b) Dapped Girder. (c) Types of Dapped Details

This paper focuses on the fatigue behavior of 90-degree, "bent-plate" dapped girder end details as examined analytically using finite element models and empirically based upon a review of fatigue failures involving the detail in service (Fry et al. 2005).

2. Dapped Girder Fatigue Failures in Japan

In Japan a dapped girder is usually referred to as a "cut-off" girder. Since the early 1960 s, dapped steel girders have been used widely in Japan; a common application has been a 90-degree rounded detail. Figure 2 is a photograph of a typical Japanese 90-degree rounded dap detail that has developed fatigue cracks. The photograph was taken in 1979 after the girder had been in service for approximately 15 to 20 years.

Figure 2. Fatigue Cracks in 90-Degree Rounded Detail in Japan

The holes visible at the ends of the fatigue cracks were drilled to inhibit further propagation of the cracks. This type of cracking behavior is typical. Generally, the cracks initiate at either the root or the toe of a fillet weld where the weld joins the web plate to the curved portion of the bent flange plate. The cracks then propagate within the web vertically and also within the web around the bent flange. The flange plate itself remains completely undamaged. Since the mid –1970 s, hundreds of instances of fatigue cracking have been reported in Japan involving this detail.

Figures 3 and 4 are photographs of a macroscopic specimen taken from a damaged 90-degree rounded detail. The cracking observed in this specimen is similar to that seen in Figure 2, though the specimen is not taken from that beam.

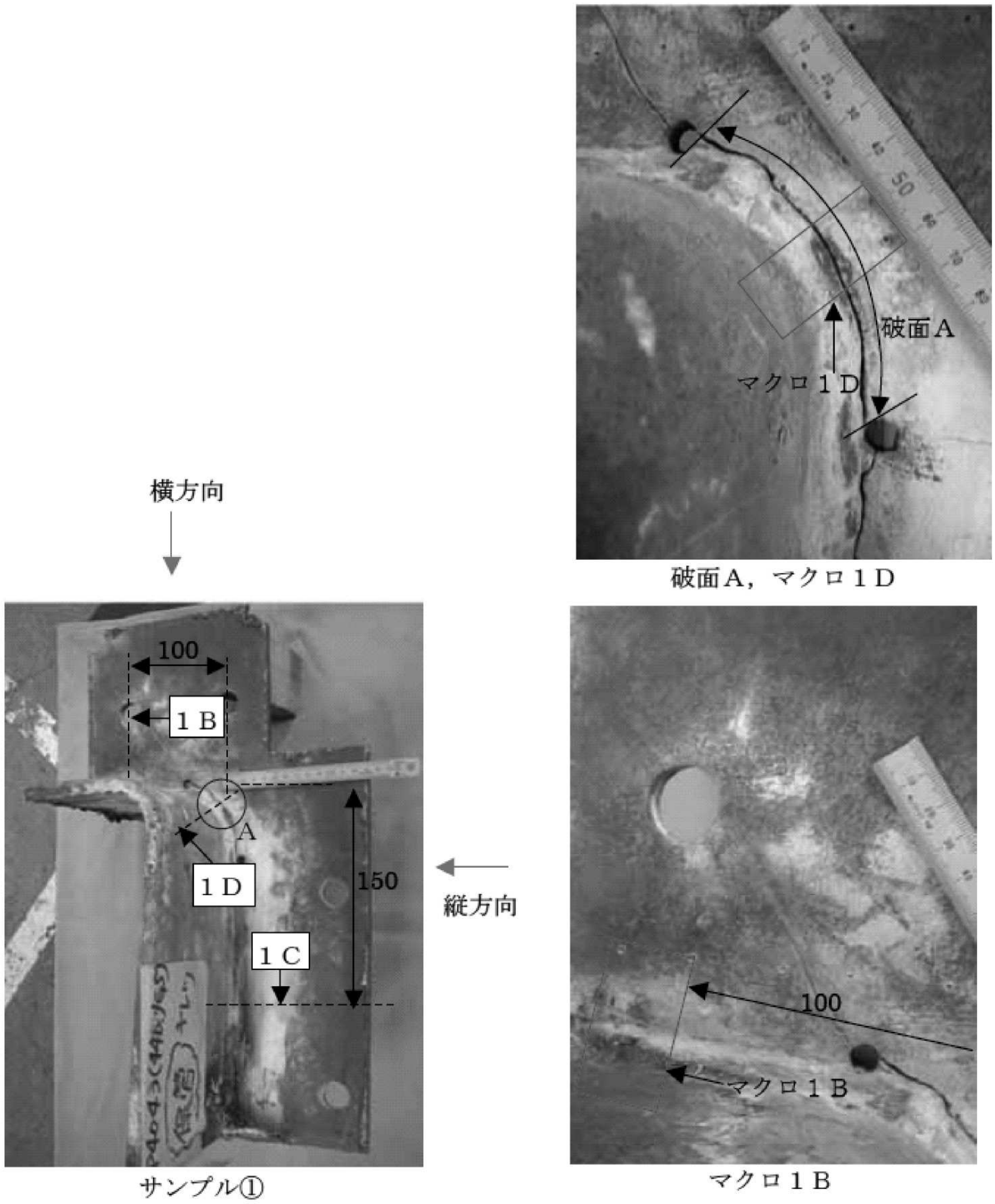

Figure 3. Macroscopic Specimen from 90-Degree Rounded Detail with Fatigue Cracks

Figures 5 and 6 show photomacrographs of different sections from the specimen shown in Figures 3 and 4. The sections have been polished and etched. The fillet welds are clearly visible in these macrographs, as are the heat-affected zones in the base metal. At section 1-C, seen in the bottom left of Figure 5, a fatigue crack is visible at the toe of the right-hand-side fillet weld. At section 1-D, seen in Figure 6, the crack has completely severed the web plate. At section 3-D, seen in Figure 6, another toe crack is visible.

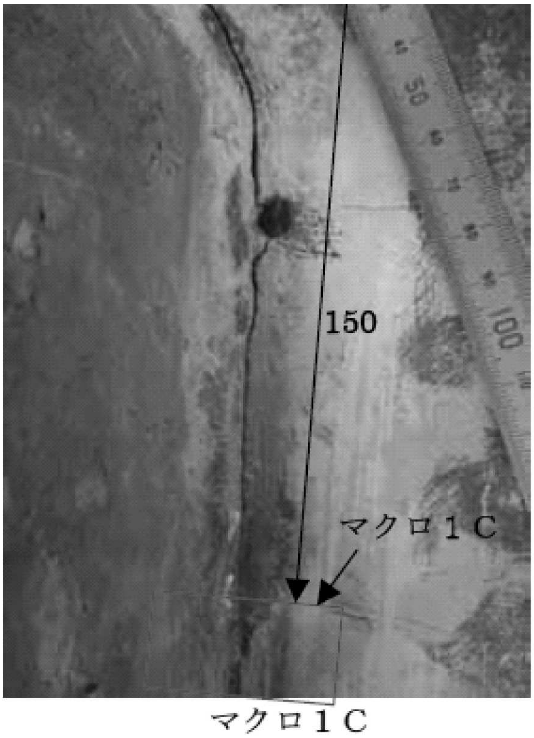

Figure 4. Closeup View of Area 1-C in Macroscopic Specimen

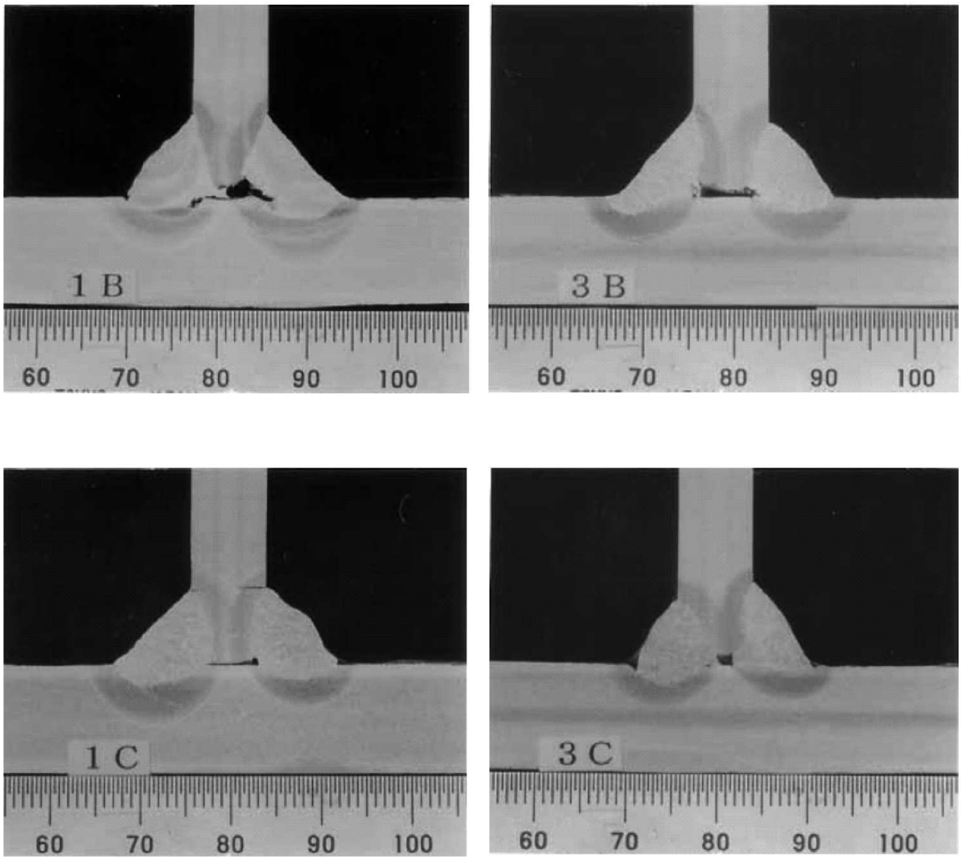

Figure 5. Photomacrographs of Etched Samples 1 and 3 (1-B, 1-C, 3-B, and 3-C)

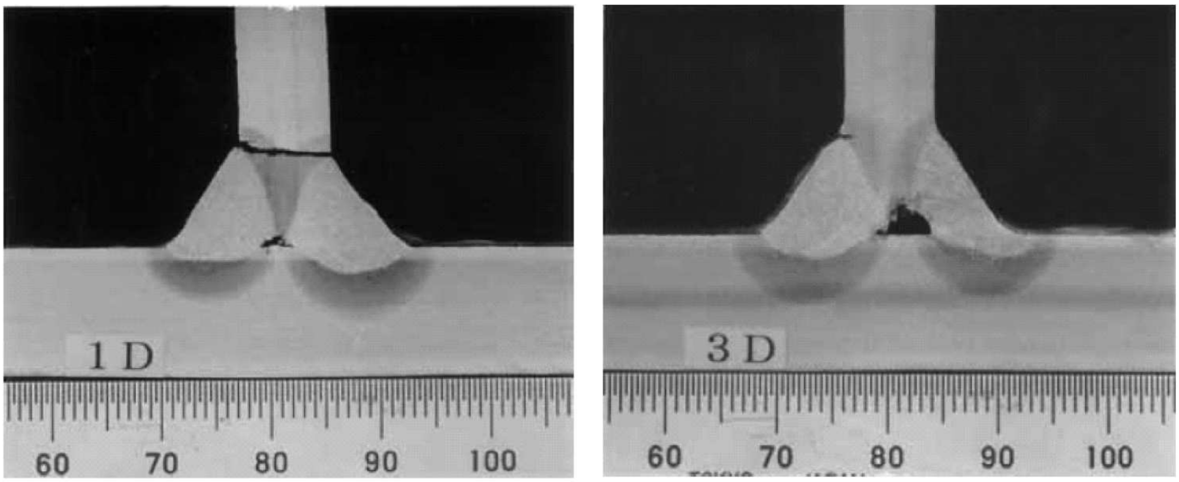

Figure 6. Photomacrographs of Etched Samples 1 and 3 (1-D and 3-D)

Figure 7 is a scanning electron microscope image of the crack initiation site on the fracture surface. The direction of crack propagation is indicated by an arrow in the image on the right-hand side of Figure 7.

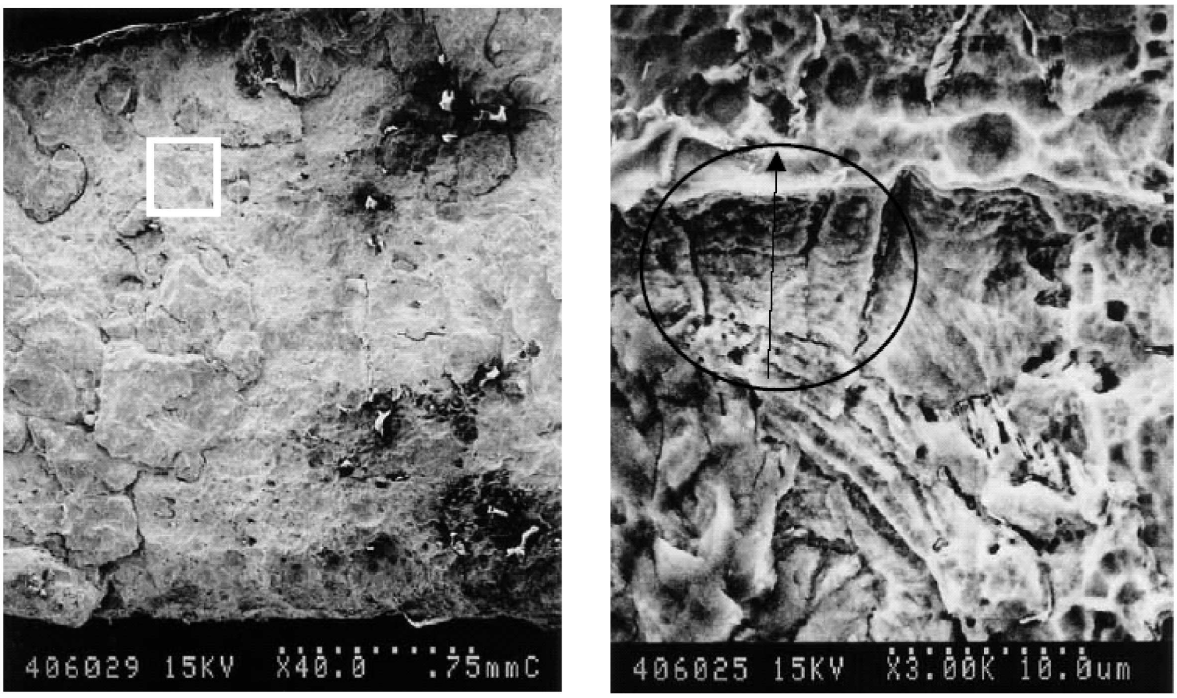

Figure 7. Scanning Electron Microscope Image of Fracture Surface.

Following the initial discovery of the cracks, analytical and experimental studies, including field tests, were conducted to determine the essential causes of the cracking. A recent summary of several fatigue applications in Japanese steel bridges is available in English (Pengphon et al. 2004). The studies suggested four potential contributing factors including the following: fabrication errors; interruption of the natural flow of stresses because of the 90 degree bend, thereby causing an unanticipated stress concentration; local out-of-plane distortions of the beam web; and inadequate rotation capacity of the beam seats because of corrosion (see Figure 8).

Figure 8. Corrosion of Beam Seat

3. Analytical Procedures

Because the dapped region of the girders is subjected to a variable-amplitude, multi-axial stress history, a special effort was required to investigate the fatigue behavior of the dapped details analytically under service load conditions. To accomplish this, three-dimensional, hierarchical finite element analyses were coupled with an advanced traffic simulation program and weigh-in-motion traffic surveys to determine local stress histories in critical regions of the dapped girders under simulated service live-load conditions. This procedure for bridge simulation was invented for this project.

In the "global" models of the bridge superstructure, shell elements modeled the girders and concrete deck. Multi-point constraints were used linking the deck to the girders to simulate composite behavior. Solid elements modeled the elastomeric bearing pads. In addition to the global models, local refined submodels of the dapped regions were constructed using solid elements. These submodels were "driven" at their edges by the displacement results from the global models after they were subjected to simulated traffic loading.

The specific wheel loads used in the simulation were determined based on a stochastic procedure calibrated against weigh-in-motion (WIM) data provided by the Texas Department of Transportation, (TxDOT 2000). The WIM data were coupled with an advanced traffic flow simulation program called CORSIM (Federal Highway Administration 1996, Aycin and Benekohal 1999, Rilett et al. 2000, and ITT 1998). With input from the three-dimensional stress histories of the solid submodels, a multi-axial, critical-plane fatigue parameter called Findley's parameter (Findley 1959) was used to quantify the fatigue demand experienced at critical locations within each of the three dapped details considered in this study. The results of these procedures to establish and compare the fatigue strength among three different dapped girder end details: notched, rounded and tapered. A detailed treatment of this procedure can be found in Fry et al. 2005.

4. Analytical Results

A total of 54 stress histories were produced using the simulation procedure described in Section 3. Stress histories are identified by the following four parameters: three dapped types (notched, rounded, tapered), three traffic periods (AM peak, off-peak, PM peak), three different truck traffic percentages (10, 20, and 80 percent trucks), and two different CORSIM link locations (link 13 and link 19). Each stress history contained values for all six independent components of the stress tensor at each deci-second of the simulation.

Findley's parameter values were calculated from the 54 available stress histories. A comparison among the magnitudes of the scalar Findley's parameter indicates which stress histories are more damaging and which dap details are more fatigue resistant. Higher Findley's parameter values mean fewer cycles to initiation of a fatigue crack. The calculated Findley's parameter values for a stress concentration region were averaged and are shown in Figures 9 and 10. As with the stress histories, the Findley's parameters are distinguished by dap type, traffic period, truck traffic percentage, and CORSIM link location.

Figures 9 and 10 show that the notched detail experienced the highest values for Findley's parameter and the tapered detail experienced the smallest values. As mentioned before, these values are inversely correlated with fatigue life; higher values indicated shorter lives. It is also interesting to note that the Findley's parameters for the tapered detail were lower than those of the rounded detail. This is a consequence of the way in which Findley's parameter is calculated. A large variation of shear stress on a critical plane causes more fatigue damage than a high mean stress level that does not fluctuate. This fact seems to imply that the rounded girder would have more fatigue problems than a tapered girder.

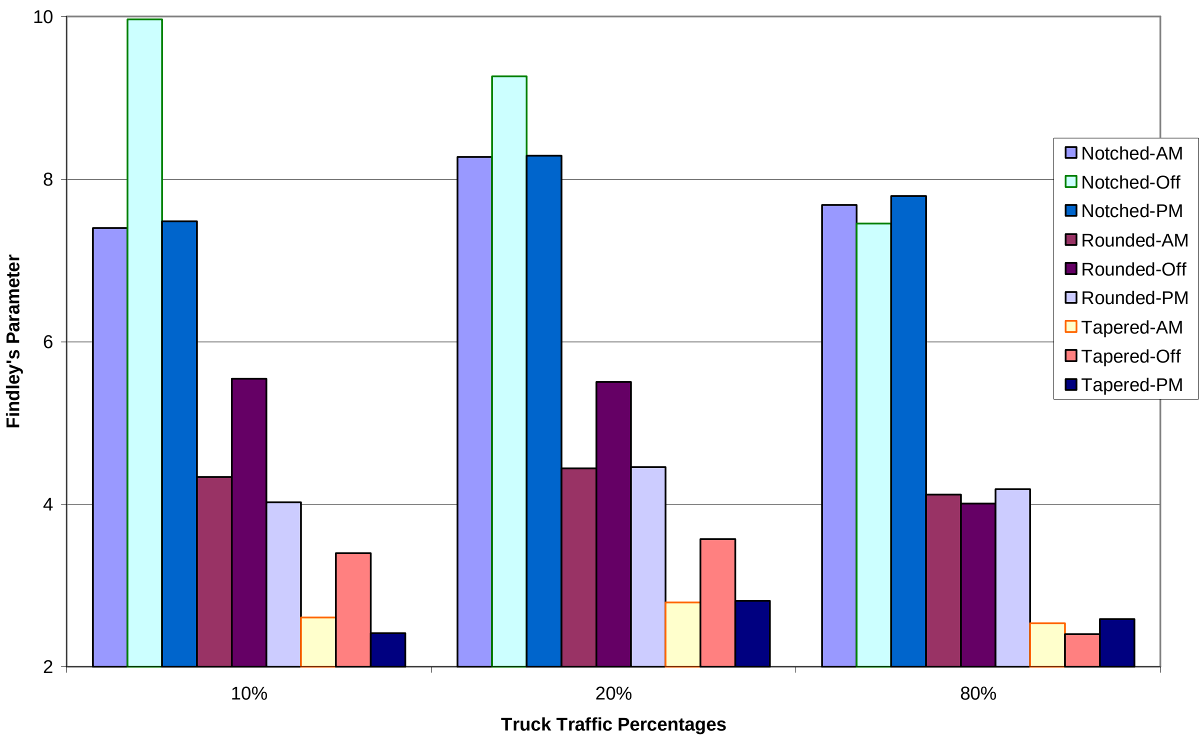

Figure 9. Fatigue Analysis Results for CORSIM Traffic Correlated to Link 13

For link 13, as shown in Figure 9, with 10 or 20 percent truck traffic, the off-peak period had substantially higher Findley's parameters for all details. This observation acknowledges the more damaging effect of a lighter volume of traffic with its associated larger range of stress. During AM or PM peak periods, heavy traffic volume loads the three-span bridge more or less evenly.

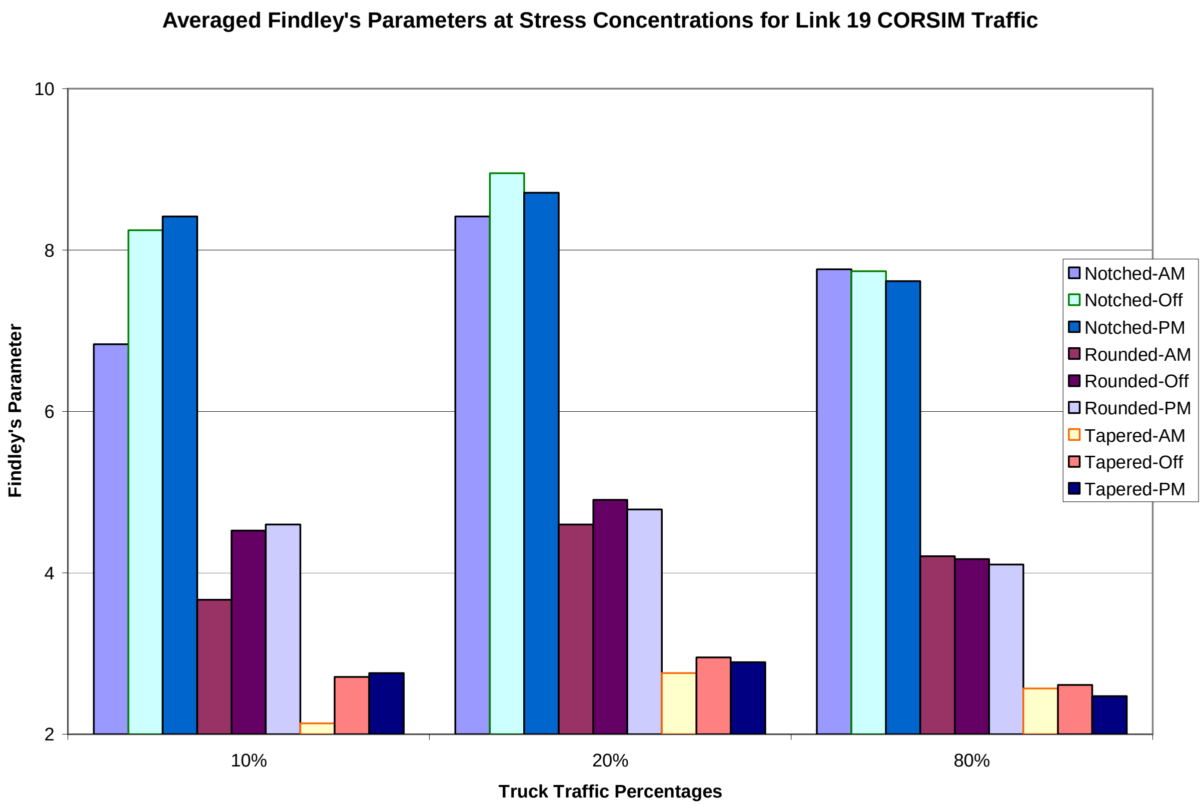

Figure 10. Fatigue Analysis Results for CORSIM Traffic Correlated to Link 19

This loading has the effect of "balancing" the stresses and creating a lower overall stress-range condition. Higher loading on one span corresponds to the analogy of loading alternate spans. In a lower volume link, with fewer trucks, and in an off-peak period, the chances of having a large difference in span loading are much greater. This phenomenon seems to be verified by Figure 10. Link 19 is a higher volume link, and Findley's parameters for the details are very similar regardless of peak period or truck traffic percentages.

Finally, Figure 11 shows stress fringe plots from a static analysis of a rounded detail similar to that used in Japan. It is clear that the regions in which the fatigue cracks were observed to initiate experience a marked concentration of stress.

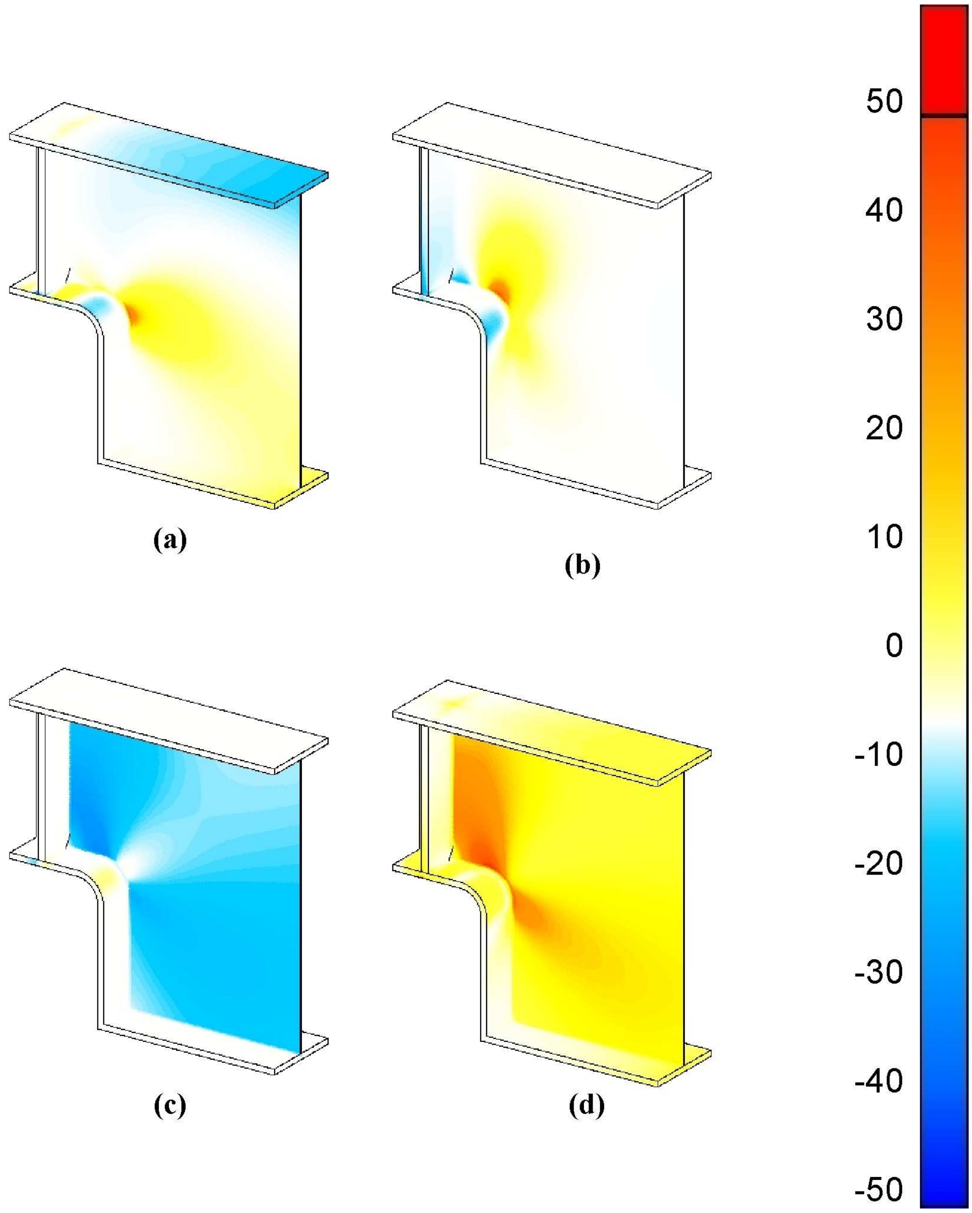

Figure 11. Stress Contour Plots of 0.5-in. Thick Web Local Models for Round Girder with No Stiffeners at Ultimate Load Capacity. (a) σ_{xx}, (b) σ_{yy}, (c) τ_{xy}, (d) von Mises Stress.

7. Conclusions

- By analysis, 90-degree rounded details possess intermediate fatigue strength when compared to notched details and tapered details.
- By analysis, two zones of local tensile stress concentration are observed in the web plate where it joins the curved flange plate: one is located between the apex of the bend and the horizontal tangent point and the other between the apex of the bend and the vertical tangent point. At both locations, the maximum principal stress is tensile and nearly perpendicular to the weld joining the web plate to the flange plate.
- By analysis, at service load levels, the addition of welded transverse stiffener plates that join the apex of the bent flange to the web neither increases nor reduces the local concentrations of stress.

- In Japan the 90-degree rounded detail has been used extensively for more than 40 years. For more than 20 years, this detail has been associated with severe fatigue problems in service involving both root and toe cracks in fillet welds connecting the web plate to the bent portion of the flange plate. As they propagate, the cracks generally form branches, some of which propagate around the apex of the bend, and others that are more severe propagate vertically through the web plate.

8. References

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