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Fatigue Failures of Steel Railway Bridges in China

Ruptures de fatigue dans les ponts-rails en acier, en Chine

Ermüdungsbrüche an Eisenbahnbrücken aus Stahl in China

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SUMMARY
This paper briefly describes the basic conditions of steel bridges on Chinese railway lines including their date of construction and the materials, technology and specifications used. Fatigue cracks are classified according to the age of the bridge at the time of their detection and then their causes analysed. Finally, examples are given of fatigue failure in bridges from every period of construction.

RESUME
Cet article donne un aperçu des ponts-rails en acier réalisés en Chine, en mentionnant leur date de construction ainsi que les matériaux, les techniques et les spécifications utilisés. Les fissures de fatigue constatées sont classées d'après l'âge de la construction au moment de leur apparition, et leurs causes sont analysées. Enfin, des exemples de rupture de fatigue de ponts sont donnés pour chacune des périodes de construction.

ZUSAMMENFASSUNG
Die technischen Bedingungen und Bauzeiten der Eisenbahn-Stahlbrücken in China (Baustoffe, Technologien und Entwurfsvorschriften) werden kurz beschrieben. Entsprechend dem Alter der Brücken und dem Zeitpunkt der Entdeckung der Ermüdungsrisse werden die Ermüdungsrisse klassifiziert und deren Ursache analysiert. Im weiteren werden Beispiele von Ermüdungsbrüchen verschiedener Altersstufen nach Charakter, Rissstellen und Ursachen untersucht.

1. The seriousness of fatigue failures

Failure accidents in the predicted service life of steel railway bridges may be attributed to the following reasons: excessive deformation, bulking, fatigue, fracture, vibration and other natural disasters. It is roughly estimated that more than 70% of the failures are due to fatigue. So fatigue is a more dangerous factor in the safety of steel bridges. According to investigations carried out by Beijing Railway Administration on 851 steel girder spans over 115 railway bridges along the Beijing-Handan Line, as many as 65 spans were found to have cracks. That is 7.6% of the total number of girders investigated (Table 1).

Table 1

Period of Construction	Spans investigated	Spans with cracks	Percentage	Percentage against the total number of cracked spans
- 1937	177	29	16.4	44.6
1937 - 1945	190	22	11.6	33.8
1946 - 1949	72	2	2.8	3.1
1950 -	412	12	2.9	18.5
Total	851	65	7.6	

To make studies of discovered fatigue cracks provides a great help to the devising of repair methods, the accumulating of experiences, the revision of fatigue design specifications and technological procedures in preventing possible future failures of fatigue. It is especially important that many Chinese old girders, which have been in use 30-40 years, were fabricated in time when fatigue concept was not yet sufficiently understood, os the fatigue problems could not be fully considered in their designs. Under the circumstances that traffic density and weight have increased by wide margins, it is no wonder that fatigue problems of various types should have appeared. Therefore it is high time to pay attention to the investigation of fatigue failures and push on the research work in calculating the fatigue life of existing bridges.

2. Basic conditions about steel railway bridges in China

In reference to construction date, the steel railway bridges may be classified into two groups:

(1) Bridge built before 1949
Most of the steel bridges erected during this period are basically steel girders from Europe, America, Russia and Japan. All of them are reveted structures of variegated low carbon steel materials including rimmed, semikilled and killed steel or even wrought iron used in earlier years. Though the majority of these bridges are still in service, some of them were strengthened, and a few were altered as a result of insufficient loading capacity or serious fatigue cracks.

(2) Bridges built after 1950
Between 1950 and 1957, China was running short of steel. Emphasis was given to the development of prestressed concrete bridges. Exceptions were a few very long span bridges which were made of imported low carbon steel, with rivet connections. The typical example for these is the Wuhan Yantze River Bridge constructed in 1957.

Since 1958 or so, our steel bridge industry has advanced on our own road. Step by step, we use home-made low carbon steel (σ_b = 412 N/mm^2), and 16Mn. low alloy steel (σ_b = 510 N/mm^2) in place of imported materials. Rivet connection has gradually given way to weld connection and bolt-and-weld connection. This transition began in 1966 when the Chengdu-Kunming Railway Line was constructed. During this period, new specifications were established. The typical examples are the Nanking Yangtze River Bridge and Ying Shuicun tied arch bridge on Chengdu-Kunming Railway Line. The latter is a large bolt-weld bridge with the span-length 112 M. In the course of developing railway bridges of longer span and lighter weight, 15 MnVN high strength low alloy steel (σ_b = 588 N/mm^2) was produced and used in conbination with 16 Mn steel on Baihe Bridge on the Shaoheng -Tongliao Railway Line in 1976. This bridge is a 3 x 128^m bolt-weld connected continuous truss.

3. Classification and formation of fatigue cracks of steel railway bridges

Fatigue cracks of steel railway bridges are caused mainly by structural stress concentration as well as defects formed in manufacturing and welding. In principle, fatigue cracks due to stress concentration can be avoided, since design specifications for fatigue have prescribed allowable fatigue stresses for different types of structural joints. It takes a long time for crack to propagate, even if the crack has appeared. But manufacturing and welding defects are difficult to predicte in fatigue design. The cracks of this kind generally appear in a short time after the structure is built. Hence, in order to explain the causes of their formations, the paper assumes to identify fatigue cracks according to the time of their appearance.

3.1 Cracks occurred in the early stage

The cracks occurred in the early stage are meant by that they are found within a few months, up to 3-5 years at most, after the structure is put in service. These cracks mostly occur at weld joints of various members in a short span beam (or members having short loaded length of influence lines). They often take place at these places where welding cracks or serious manufacturing and welding defects have already existed.

It is known to all that the most important factors causing fatigue cracks are the number of stress cycles and the distribution mode of stress frequency. The former is related to the type of train load and calculated girder span or loaded length of influence line of the member concerned.The latter is influenced by the magnitude of the wheel load, in addition to the above mentioned factors. Field measurements show that, in case of long span girders (> 30 M), the girder is subjected only to a single stress cycle during the passage of a train. As for short span girders, under the loading action of a passing train, the number of stress cycles varies with the number of axles and the number of bogies the shorter the span, the greater the number of stress cycles. It is clear from the above statement that though the stress level in short span girders caused by the axle load of a train is generally low, even lower than the fatigue limit of the joint, and has little consequence upon the formation of fatigue crack, but it plays an active part in the propagation of an existing weld crack. What is more, the greatly increased number of stress cycles speeds up the propagation of the crack. This is the major cause which accounts for crack propagation taking place in a very short period of time in the case of short span girders with weld cracks.

3.2 Fatigue cracks occurred after a long service period

This form of cracks is referred to those which occur after the structure has been used for ten years to several decades. The causes of formation of such

cracks may be mentioned as follow:
— The train density and train load have greatly outpaced the original design loading.
— The design of certain structural details has not been considered comprehensively.
— The manufacturing technology and machining precision are not up to the design requirements.
— There are out-of-plane deformations which have not been considered in the design, and secondary stresses generated as a result of restraint imposed upon the deformations.
— Fairly high auxiliary stresses are generated at certain locations due to abnormal displacement of bridge bearings.

These fatigue cracks generally go through a complete formation process (metallurgical crystal lattice slide — microscopic crack — macroscopic crack --crack propagation). The time traversed under such circumstances will be much longer than that with weld cracks.

4. Case study of fatigue failures of steel railway bridges in China

The following are some typical examples of different kinds of cracks on steel railway bridges constructed in different historical periods.

4.1 Brittle fractures caused by repair welding

Bridge No. 248 on the Beijing-Baotou Railway Line was a rolled I-beam bridge which was manufactured in Britain in 1898 and erected in 1903. Its original length was 7 M and was cut down to 4.6 M in 1947 to be used as a simple span. There were four drilled holes of Ø19 on the webs and two on the bottom flanges. These holes were filled later by gas welding when it was cut. It so happened that at about 11 o'clock in the mroning of November 30, 1967, after a heavy snow fall, a large piece of flange metal broke off together with a portion of the web. Fig 1 is a sketch of the girder and the failure location. Photo 1 is the fallen off piece. From the fracture surface, we could find that the weld quality was very poor. Under repeated action of train load through a long period of time, fatigue crack was initiated at the notch (Photo 2).

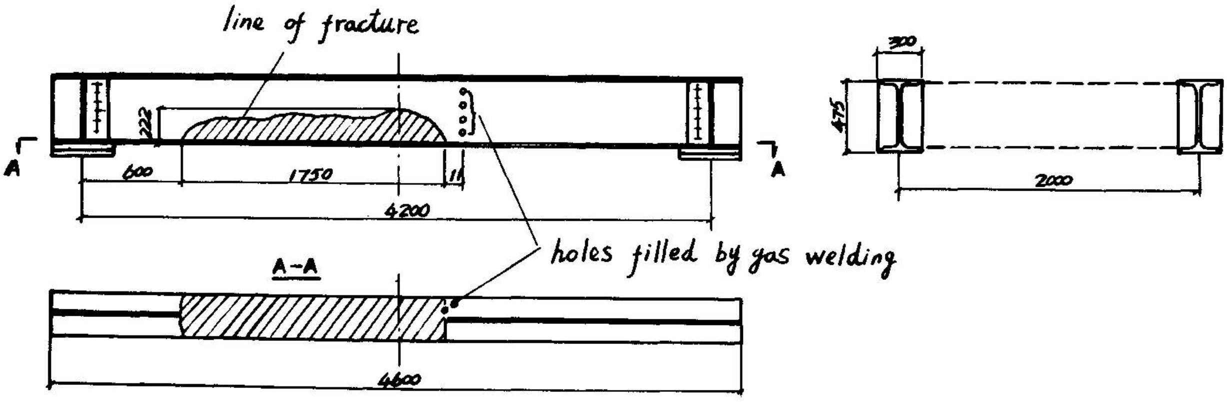

Fig 1 Sketch of the girder bridge No. 248 and its failure location

Samples were taken from the girder for chemical analysis and mechanical test. The steel strength was equivalent to that of the carbon steel but was high in S, P and N content which made it difficult for welding. The ductility of the material at low temperature was rather poor and the ageing effect tendency was quite strong. U-notch impact test showed that the brittleness transition temperature was about +15°C - 0°C.

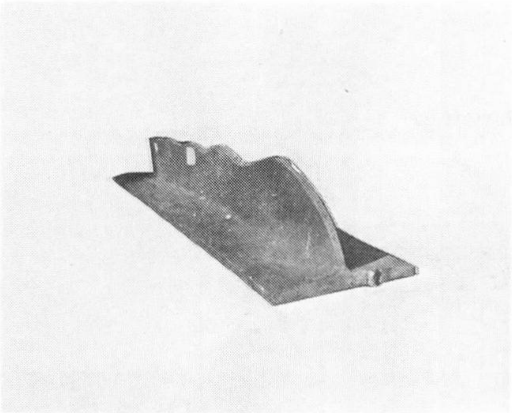

Photo 1 The fallen off metal of bridge No. 248

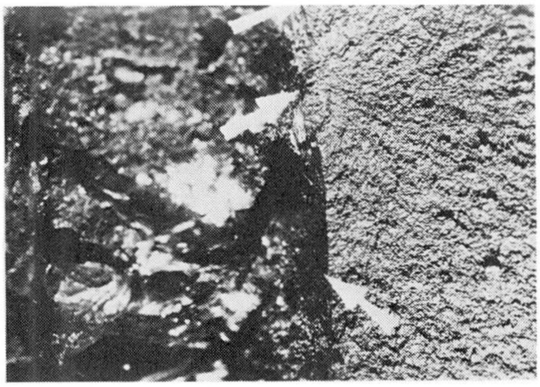

Photo 2 Fatigue crack at the notch of bridge No. 248

This accident once more teaches that direct repair welding on steel girders must be strictly forbidden. Otherwise it would be very much likely that weld defects or weld cracks should appear and deterioration, a decrease in ductility in particular of the weld metal and the heat affected zone would happen. And these would certainly give rise for the formation of fatigue crack and brittle fracture. This is an important problem we must pay attention to in the reconstruction and maintenance of bridge in the future.

4.2 Fatigue failures at riveted joint

One accident of this kind took place on Taizi River Bridge on the down line of the Changchun-Dalian Railway. It was a 17 span simple through truss bridge.

On March 23, 1973, the fracture occured at the upper panel point of the first diagonal of the 16th truss built in 1930, with a span length of 33.54 M. Photo 3 show the location of the fracture.

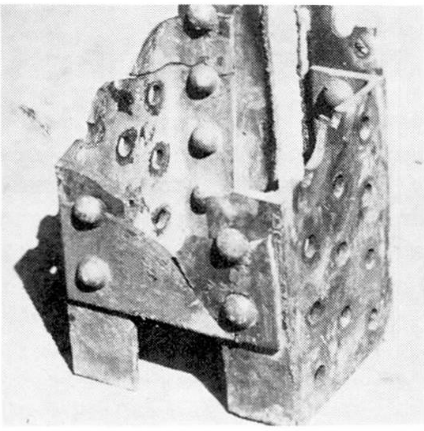

Photo 3 The form of the fracture member of Taizi River Bridge

Field investigation revealed that fatigue crack took place at an early stage in one of the diagonal channels. The other channel was pulled to break with obvious appearance of a bottleneck. The causes of the formation of the fatigue cracks are as follows:

At the time of design 50 years ago, the fatigue behaviour of the riveted joints was not clearly understood. The present train load and train load and train density (about 80 trains per day) on the bridge were much greater than those when the bridge was first constructed. The lateral bracings were too weak, so the passing trains caused the truss to produce great vibration in the horizontal direction.

4.3 Fatigue cracks caused by improper detailing

In Fig 2 is indicated the fatigue cracks occuring at the angles connecting the end cross beam and the main truss. In the original design, the bottom flange of the end cross beam was placed directly against the bearing plate so that the reaction force might be partly transmitted through the plate. However, after many years of operation, a gap of 2-3 MM was formed between the bottom flange of the cross beam and the top of the bearing plate, which had deformed and worn out. As a result, the line of transmission of the reaction force was so altered that the stresses in the connecting angles were greatly increased. This was the major cause of the fatigue cracks.

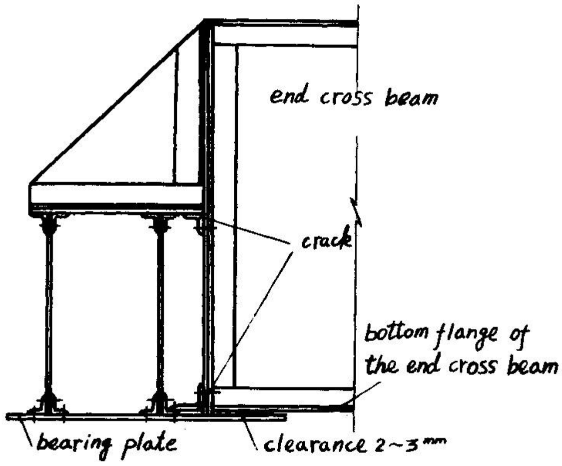

Fig 2 Fatigue cracks occuring at the connecting angles

4.4 Longitudinal fatigue cracks on the upper flanges of plate girders directly supporting wheel load

In some old-type riveted girders, both the upper and lower flange cover plates were provided in conformity to the moment diagram. Some of them often stopped at a distance from the bridge support. The flange plate between the support and stopped point was rather thin (8 MM only), but it cantilevered out as many as 110 MM (Fig 3). This was why longitudinal fatigue cracks often took place at this location. The two major causes of the formation of this longitudinal fatigue cracks are: (1) high impact forces under the direct train wheel load. (2) Transverse deflection of the upper flange induced by the vertical deforation of sleeper under train load. The beam action of sleepers on D.P.G. Bridges arose from a difference that existed between the center to center distance of the main girders which was 2 M and the gauge distance of the rails which was 1.435 M.

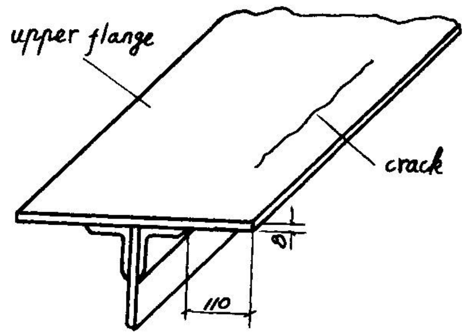

Fig 3 Crack on the upper flange

4.5 Cracks at the toe of fillet weld of vertical stiffeners of stringer of truss bridges

Langjiang Bridge on the Changsha - Liuzhou Railway Line, which was completed and opened to traffic on November 28, 1964, was the first bolt-weld railway through truss bridge using 16 Mn steel, with a span length of 61.44 M. One hundred days later, a horizontal crack was observed right beneath the manual weld, which connected the semi-automatic welds on both sides of stiffener, at the end of the center stiffener of stringers on March 8, 1965 (Fig 4).

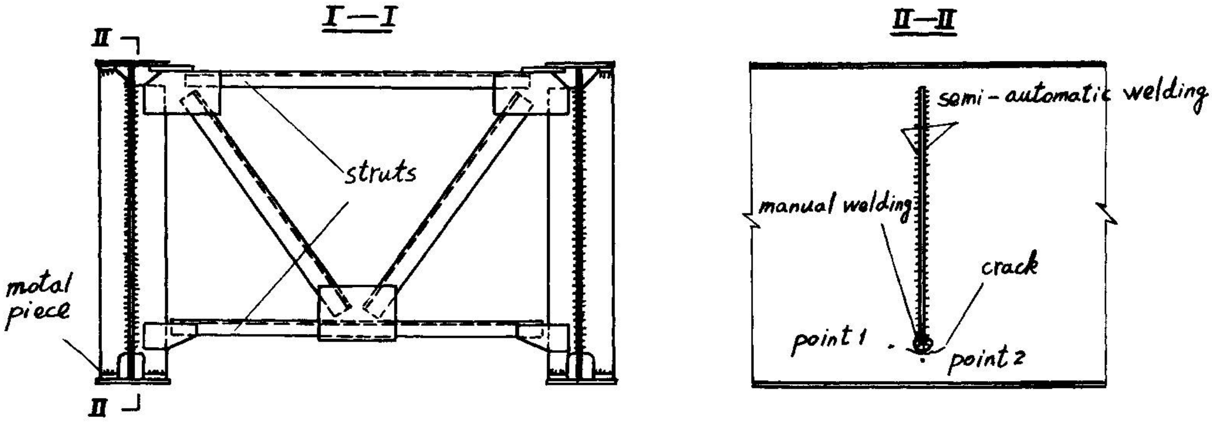

Fig 4 Crack at the end of the center stiffener

After the crack was revealed, the stringer was subjected to a test. Test result showed that, under the long-term action of train load, the metal pieces, which were inserted in the gaps between the stiffener ends and flange, could hardly keep bearing tight against the flanges. It was obvious that this type of structural detail would not meet the design requirements. In such a case, the vibration frequency measured on point 1 and 2, near the lower end of the center stiffener, was about 30 HZ, this location produced great vibration as the train passed. The maximum alternate stress at point 1 was observed to be $^{+}45.6$ and -31.0 N/mm^2. However, when the bottom flange of the stringer and the bottom lateral bracing of the truss were held rigidly together, the vibration frequencies at point 1 and 2 were measured to be 40-50 HZ and the alternate stress reduced to less than ±4.9 N/mm^2.

Furthermore, out-of-plane deformation and angle of rotation are produced in the stringer under the action of train load. The additional flexural stresses were induced at the lower end of the vertical stiffener.

In addition to the above considerations, the welding technologies used for the vertical stiffeners of the stringers were unfit. Employing manual welding to connect the semi-automatic welds on both sides of the stiffener was apt to produce welding defects instead of any favourable effect. It may be concluded that the horizontal crack or under cut (even it was very fine) at the lower end of the vertical stiffener welds would propagate very fast under the action of the above-mentioned additional stresses.

Since the Langjiang Bridge accident, the constructional detail of the stiffener and the strut hastbeen modified. The lower strut of cross brace, instead of being connected to the lower end of the vertical stiffener, was made to connect to the bottom flange of the stringer through gussest plate. Furthermore, 16Mn low alloy steel was used to make the stringers, the height of which was thus reduced from 1,450 to 1,290 MM. After these modifications, no fatigue problem has been encountered at this location.

4.6 Welding cracks on the fillet welds of stringer flanges of girder bridges

The Puyanjiang Bridge on the Hangzhou-Nanchang Railway Line is a half-through girder bridge with a total length of 166.9 M. The third span is 34.75 M in length. The girder was made in September, 1975 and opened to traffic in 1976. In July, 1979, the first crack was found at the toe of fillet weld of a stringer. Eleven cracks at similar locations of the bridge were found in latter inspection. The most serious one appeared at the fillet weld near the end of the upper flange of the stringer in the 8th panel. The crack ran 25 MM along the toe line and then turned an angle of 30°into the web 17 MM (See Fig 5).

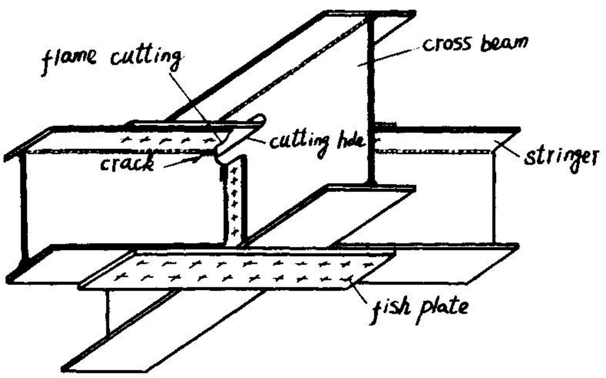

Fig 5 Cracks at the toe of filled welds of stringer flange and connecting plate between cross beam and stringer.

During manufacture, flame cutting of the flanges and the web was done in one operation. The cut face was not machined nor ground with disk sander. Its zigzagged outlook showed that the cutting quality was very poor and did not meet the need of design. Considering the location of the crack, its tendency and course of propagation, and the length of service time, it is quite possible that crack(1) owes its origin from the toe crack which developed under the effect of thermal stress during flame cutting accompanied by a complicated state of residual stresses induced around the crack. As a result, under the train load, first of all developed into the web plate, and then extended along the direction normal to the principal stress in the web.

4.7 Cracks at the toe of fillet weld connecting horizontal bracing with gusset plate

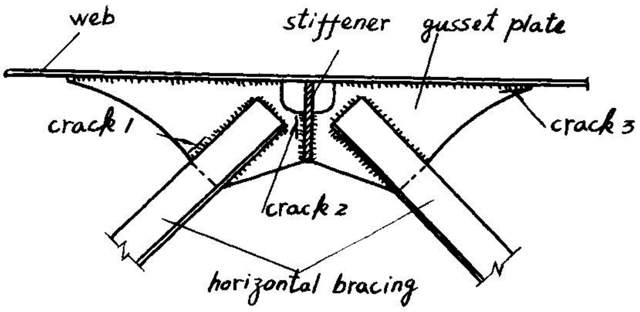

Fig 6 Cracks at the toes of fillet welds of the gusset plate of horizontal bracing

Fig 6 shows the cracks found at the welds of the gusset plates of the horizontal bracing on the deck girder bridges of 22.0 M span in the Shenyang Railway Administration. These bridges were erected after being fabricated in 1974-1975. Very soon thereafter, the cracks were generally found. During an overall inspection in April, 1976, cracks of this kind were found at as many as 29 places on five of the 22.0 M span girders on the No.3 Anshanhe Bridge on the Changchun-Dalian Railway Line. It was more than four years from the cracks found up to now, they did not propagate. These cracks, in the main, were essentially welding cracks at the toe of weld.

4.8 Cracks in the weld connecting horizontal and vertical stiffeners

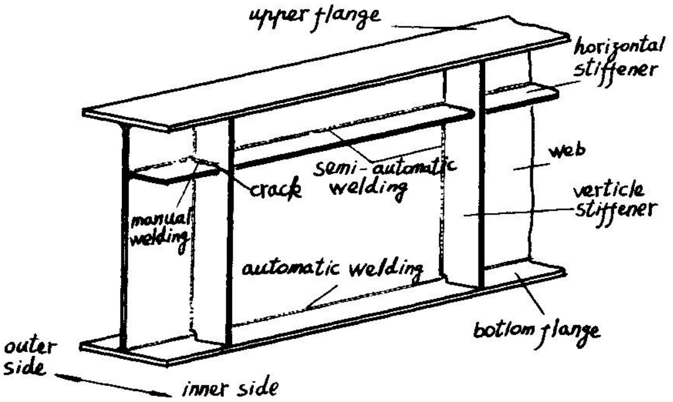

Fig 7 Cracks in the welds connecting horizontal and vertical stiffeners

Fig 7 shows the crack found at the toe of weld connecting the horizontal and vertical stiffeners on welded deck girder bridges. To avoid this kind of welding cracks, aside from that it is essential to select the right type of welding rod, to strictly control the baking temperature of the rod so as to reduce its hydrogen content, to reduce the assembly tolerance as much as possible, and to clear the steel plates of rust, it is also advisable to modify the structural details and to rearrange the welding sequence. The horizontal stiffener can be made with a whole piece of the same length as the web passing through the notches of the vertical stiffeners, and weld up the stiffeners after assembling before other welds are done. An alternative is to leave the horizontal and vertical stiffeners unwelded as arranged in the above-mentioned manner.

5. Conclusion

From the preceeding representative cases of fatigue fractures, it can be seen that the periodical inspections of old bridges become highly necessary. The probability of fatigue crackes occurring within a short period of service time has substantially increased on welded steel bridges with short spans in particular. The fact shows that welding cracks, particularly cracks at the toe of the weld, deserve proper attention even though they exist only in a small amount. For repair of indicated cracks, welding is not preferred. Experience has shown that high strength bolt is a better resort for repair of fatigue cracks and for strengthening of steel girders.