FAILURE ANALYSIS OF THE HANGER CLAMPS OF THE KUTAI-KARTANEGARA BRIDGE FROM THE FRACTURE MECHANICS VIEWPOINT

Yutaka KAWAI¹, Dionysius SIRINGORINGO² and Yozo FUJINO³

¹Fellow of JSCE, Part-time Lecturer, Dept. of Civil Eng., Nihon University
( Izumicho1-2-1, Narashino, Chiba 275-8575, Japan)
E-mail: Yutaka-kawai@mue.biglobe.ne.jp
²Member of JSCE, Project Assistant Professor, Dept. of Civil Eng., University of Tokyo
(Hongo 7-3-1, Bunkyo-ku, Tokyo 113-8656, Japan)
E-mail: dion@bridge.t.u-tokyo.ac.jp
³Fellow of JSCE, Project Professor, Dept. of Civil Eng., University of Tokyo
(Hongo 7-3-1, Bunkyo-ku, Tokyo 113-8656, Japan)
E-mail: fujino@sogo.t.u-tokyo.ac.jp

On November 26, 2011, the Kutai-Kartanegara Suspension Bridge in Indonesia collapsed. The collapse was triggered by failure of the clamp of cable band that connects the hanger with the main cable in the middle of the centerspan. The national investigation team report cited the failure as a result of stress accumulation on the clamps that have been weakened by fatigue, initial fracture and corrosion. In this paper, we investigated in more detail the possibility of shear brittle fracture of the clamp’s pin from the viewpoint of linear fracture mechanics by utilizing the measured Charpy absorbed energy. Several possible scenarios of defect sizes and combined stress conditions were assumed. The analysis shows that the shear brittle fracture could occur even under low shear stress level when several unfavorable conditions occur simultaneously.

Key Words: cable band, clamp pins, shear failure, linear fracture mechanics, brittle fracture

1. INTRODUCTION

The report of the national investigation team on the collapse of the Kutai-Kartanegara Bridge, the longest suspension bridge in Indonesia, released in January 2012, revealed that an accumulation of design faults, negligence in service and restoration work had sequentially caused the bridge collapse. In particular, the report emphasized on the stress accumulation of the hanger clamps as the triggering mechanism of the collapse. Post-accident investigation of the clamps has shown that they may have been weakened by corrosion or cracking and fatigue (Fig. 1). The report also questioned the selection of high-strength ductile iron FCD-600 that has low-energy impact absorption and poor toughness as material for the clamps.

Based on information on the bridge design document, the accident investigation report and field survey conducted by the second author immediately after the accident, we shared the view of the national investigation team that performance of clamp should be considered as possible cause of the collapse. However, in our opinion, such conclusion should be supported by a fracture surface analysis, and such analysis, to the best of authors’ knowledge, has not
been performed. The main part of the hanger clamp from the middle of the center span that triggered the bridge collapse fell into the river, while the parts were still attached to the suspension cable and remained inaccessible for analysis.

Since the collapse was initiated by the clamp failure, the present study focuses on structural performance of the clamp by investigating the load transfer mechanism, material and strength of the clamp. In this note, we investigate the possibility of brittle fracture of the clamp from the linear fracture mechanics viewpoint. The fracture toughness of the clamp was estimated using results from the Charpy Impact values obtained from material test of the remaining clamps. The possibility of brittle shear fracture was examined by assuming some initial crack-like defects at the base of pins and by considering fracture toughness of the material under the influence of combined tensile and horizontal axial force on the clamp. Furthermore, the effects of the axial tensile stress that were not considered in the design calculation, on the possibility of brittle fracture due to combined shear and axial stresses were discussed.

### 2. DESIGN STRENGTH OF THE CLAMP PINS

Ductile cast iron FCD 600-3 was used for the clamp. The pin of the hanger clamp was cast together with the cable band as shown in Fig. 2. The pins, placed on both sides of the main cable’s band, were designed to resist shear force caused by axial load on the hanger, and the shear strength was calculated in accordance with AASHTO LRFD 1) as follows:

**Yield condition:**

\[ R_{P,y} = \phi \cdot A_p \cdot f_{y,P} \]  

**Ultimate fracture condition:**

\[ R_{P,u} = \phi \cdot A_p \cdot f_{u,P} \]  

Here, \( A_p \) denotes the cross-sectional area of the pin, \( f_{y,P} \) and \( f_{u,P} \) denote the yield and ultimate tensile stress of the pin, respectively, and \( \phi \) is the strength reduction factor. Diameter of the pin is \( D = 73 \) mm. In the design, the \( f_{y,P} \) and \( f_{u,P} \) were 370MPa and 600MPa, respectively. However, from the laboratory test of the specimen, the actual values of \( f_{y,P} \) and \( f_{u,P} \) were found to be 595MPa and 781MPa, respectively.

Table 1 shows the measured values obtained from the laboratory test of a damaged clamp specimen and comparisons with mechanical properties of the standard material (FCD 600-3).

In the retrofit work plan 3), the maximum jacking load on the hanger was limited to 595kN (60.72tonf) and the shear stress on the pin was considered to be 150MPa. If the retrofit work was carried out as planned, then shear forces acting on the pin during the jacking would have not exceeded about 1/3 of the actual ultimate strength (based on the tensile strength of the specimen test). Even after taking into account the coefficient of non-uniform shear force of 2.0 and the reduction of cross section due to possible corrosion and fatigue cracks, it was unlikely that ductile shear failure had taken place.

Therefore, we investigated the possibility of brittle shear failure, by assuming the existence of an initial crack-like defect as will be described below.
3. ESTIMATION OF FRACTURE TOUGHNESS OF CLAMP MATERIAL (FCD 600-3)

As explained in Table 1, JIS G 5502 does not specify the Charpy impact value requirement for material FCD 600-3. The result of material testing of the damaged clamp provides the Charpy impact value ($v_E$) of 4.27 J. In reference 4), it has been reported that FCD400 material tested in room temperature ($20 \degree C$) can have the Charpy impact value of 15-20 J. In the specification of material FCD-400 there is a provision for minimum impact value of 14 J. Judging from the test results, one can clearly see that the FCD-600 used as the clamp material indeed has low material toughness. The Charpy impact value can be used to determine ductility of a material; however, basically it does not have theoretical relation with fracture mechanics. From the fracture mechanics point of view, we must use fracture toughness performance index such as $J$ integral ($J_r$) and linear fracture toughness ($K_C$) to describe the possibility of brittle fracture.

In this investigation, the only available information on toughness of the material was the Charpy impact value obtained from the laboratory test of the damaged clamp. Therefore, using this value an attempt to estimate fracture toughness $K_C$ was sought to examine the condition for brittle fracture of the clamp by linear fracture mechanics approach.

There are three types of crack propagation under different loading conditions (Fig. 3), namely opening (Mode I), in-plane shear (Mode II) and out-of-plane shear (Mode III). Shear failure of the pin of the clamp can be categorized as mode II. Among the three modes, empirical formulations to estimate $K_C$ using the Charpy impact value for opening mode (i.e., $K_{IC}$ for mode I) have been proposed in numerous studies. However, not so many studies have proposed the formulation for in-plane shear (mode II).

Several studies have proposed empirical formulations to estimate $K_{IC}$ from the Charpy impact value depending upon the chemical composition of the steel and the steel yield strength. Bannister\(^7\) proposed a direct relationship between Charpy impact value $v_E$ and linear fracture toughness $K_{IC}$ as:

$$K_{IC} = 19\sqrt{v_E} \left( K_{IC} : \text{MPa} \sqrt{\text{m}}, \quad v_E : \text{J} \right) \quad (3)$$

Barsom and Rolfe\(^6\) proposed the following empirical relationship for steel material with yield strength between 760 and 1700 MPa:

$$\left( \frac{K_{IC}}{\sigma_y} \right)^2 = 0.64 \left( \frac{E}{\sigma_y} - 0.01 \right) \quad (4)$$

Roberts and Newton\(^7\) proposed the following relation:

$$K_{IC} = 0.54 \sigma_y E + 55 \left( K_{IC} : \text{MPa} \sqrt{\text{m}}, \quad v_E : \text{J} \right) \quad (5)$$

In the INSTA Technical Report\(^8\), the relationship between fracture toughness and the Charpy impact value for a reference plate thickness of $t = 25$ mm is described as:

$$K_{IC, 25} = 12\sqrt{v_E} \left( K_{IC} : \text{MPa} \sqrt{\text{m}}, \quad v_E : \text{J} \right) \quad (6a)$$

while for any $t$ thickness of the plate, relationship becomes:

$$K_{IC, t} = \left[ (K_{IC, 25} - 20) (25/t)^{0.4} \right] + 20 \quad (6b)$$

For rolled steel plate carbon with the yield stress of about 235-323 MPa, Yajima et al.\(^9\) proposed the relationship between fracture toughness and Charpy impact value as:

$$K_{IC, t=50} = 40\sqrt{v_E} \left( K_{IC} : \text{MPa} \sqrt{\text{m}}, \quad v_E : \text{J} \right) \quad (7)$$

where $\sigma_{YO}$ is the specified yield point of the base material in kgf/mm\(^2\). $K_{IC, t=50}$ is the fracture toughness at $t$ (mm) thickness plate, and $v_E$ is the Charpy impact value. Note that 1 kgf-mm\(^3/2\) = 0.31 MPa$\sqrt{\text{m}}$ and 1 kgf-m = 9.8 J.

Expressions and relationships used in the above-mentioned studies are typically for material with large Charpy impact value at room temperature. Therefore, question remains on the applicability of the formula on material with low fracture toughness (about 4) as measured from a test of the clamp.

Nevertheless, Table 2 shows the values of fracture toughness for Mode I estimated by the above formula. And despite some variations, the estimates are generally within the range of 40-60 MPa$\sqrt{\text{m}}$.

Therefore, in the subsequent analysis we assume the lowest $K_{IC} = 40$ MPa$\sqrt{\text{m}}$ as the representative value.

It should be noted, however, that the fracture toughness values are only for load shape opening
mode I, while the shear failure of the pin is, in fact, an in-plane shear opening (mode II). Therefore, we need to consider the relationship between fracture toughness of in-plane shear opening (mode II) and that of the load shape opening mode I.

The relationship between \( K_{IC} \) and \( K_{IIC} \) had been investigated by many researchers and the results varied depending on the test temperature and steel grade. Erdogan and Sih\(^{10}\) reported the value of \( K_{IC} / K_{IIC} = 0.71 \) obtained by the maximum tangential stress theory as one of the criteria for brittle fracture. From an investigation on 0.04% carbon steel, Yokobori et al.\(^{11}\) suggested \( K_{IIC} / K_{IC} = 0.7-0.9 \). Shih\(^{12}\) suggested the value of \( K_{IIC} / K_{IC} = 1.09 \). From the test on HT50 at room temperature, Takamatsu and Ichikawa\(^{13}\) suggested the value of \( K_{IIC} / K_{IC} = 0.95 \). Therefore, in the following, we compare the fracture toughness of mode I and mode II under \( K_{IIC} / K_{IC} = 0.7 \) and \( K_{IIC} / K_{IC} = 1 \) as two extreme conditions.

### 4. ANALYSIS ON THE POSSIBILITY OF BRITTLE FRACTURE ON THE PIN

The precise loading conditions of the hanger rods during retrofit work remain unknown, since the exact amount of force that had been transferred during the jacking process remains unknown. Moreover, fracture surface analysis on the clamp that triggered the collapse could not be carried out, since parts of the cable band and pin clamp on the center of the span were still inaccessible, while the hanging bar and side arms had fallen into the river.

In the following, we shall discuss the cause of shear failure at the base of the pin by assuming 595.06 kN as the loading condition that is the maximum limited load of jacking work as indicated in the retrofit work plan. Analysis is conducted by assuming the worst load scenario that is eccentric load only on one side of the side arms, and that shear strength of the pin is as described in the Statement Summary of design calculation\(^2\).

It should be noted that ductile shear fracture occurs when the shear force applied on the net sectional area of the pin (i.e., effective sectional area after considering corrosion loss or fatigue crack propagation) is equal to the hanger load. On the other hand, brittle shear fracture occurs when the stress intensity factor on the tip of the crack-like defect of the in-plane shear crack (mode II), denoted as \( K_{II} \), is equal to or greater than the pin material fracture toughness (\( K_{IIC} \)).

To calculate the \( K_{II} \), FEM analysis is normally employed\(^{16}\). However, since we focused on examining schematically the possibility of shear brittle fracture of the pins, an approximate expression for the stress intensity factor \( K_{II} \) for a bar having a surface crack was considered reasonable amid the complexity of FEM analysis\(^{15}\). For approximation, the stress intensity factor on a cracked rectangular cross-section, instead of circular section given as the following equation\(^{16}\), was applied.

\[
K_{II}(\alpha) = F_{II}(\alpha) \cdot \frac{\tau}{\sqrt{\pi a}} \quad (8)
\]

where

\[
F_{II}(\alpha) = 2.13 - 11.03\alpha + 35.01\alpha^2 - 59.44\alpha^3 + 52.09\alpha^4 - 17.73\alpha^5
\]

(9)

In the expression above, \( \tau = P/A, \alpha = a/D, P \) denotes the axial load in the hanger rod, \( A \) is the cross-sectional area of the pin, \( a \) is the crack depth and \( D \) is the height of the pin.

The cross-sectional area of the pin base is designed only for shear forces due to vertical load acting on the hanger rod. However, as shown in Fig.3, both ends of the pin are clamped by a washer and nut to prevent it from getting out of the side arms. When horizontal force is applied on the hanger rod, as shown in Fig.6, the acting force will induce not only shear but also normal stress. This means stress evaluation under combined forces is required. In such a case, stress intensity factor of the round bar with surface crack is given by the following equation\(^{17}\).

\[
K_{II}(\alpha) = F_{II}(\alpha, \beta) \cdot \frac{\sigma}{\sqrt{\pi a}} \quad (10)
\]

where

\[
F_{II}(\alpha, \beta) = \left(1.122 - 0.230\beta - 0.901\beta^2 + 0.949\beta^3 - 0.280\beta^4\right) \times \left(1.0 + 0.314\alpha - 2.536\alpha^2 + 36.72\alpha^3 - 106.048\alpha^4\right)
\]

(11)

Note that \( \alpha = a/D \) and \( \beta = a/h \), where \( a \) denotes the crack depth, and \( 2b \) denotes the surface crack width. However, the formula applies only to \( \alpha \leq 0.25 \) and \( \beta \leq 1.0 \).
The critical condition for the occurrence of brittle fracture under such combination of loading mode is generally represented by the effective stress intensity factor $K_{\text{eff}}$ as follows:

$$K_{\text{eff}} = \sqrt{K_I^2 + K_{II}^2 + \frac{1}{1-\nu} K_{III}^2} \leq K_C$$  \hspace{1cm} (12)$$

Since the possible rotation of the side arms and the pin is small, the out-of-plane shear load due to torsional loading in the above equation can be ignored. Hence, $K_{III} = 0$ and the condition for brittle fracture for mode II under combined axial and shear forces becomes:

$$K_{II} = \sqrt{K_C^2 - K_I^2} \leq K_C$$  \hspace{1cm} (13)$$

From the above equation, the crack depth $a$ and the critical shear stress $\tau_{\text{cr}}$ for the occurrence of brittle fracture is given as:

$$\tau_{\text{cr}} = \frac{K_C^2 - K_I^2}{F_{II} \cdot \sqrt{\pi a}}$$  \hspace{1cm} (14)$$

Fig.5 and Fig.6 show the calculated relationship between the brittle shear strength of the pin $R_{uc}$ and crack depth $a$ for the varying normal tensile stress $\sigma_t$ of the pin for $K_{II}/K_C=1.0$ and $K_{II}/K_C=0.7$, respectively. The figures also plot the relationships between ductile shear strength and crack depth. Note that applied normal tensile stress was not considered in the original design of the pins and these stress conditions were only assumed. In these figures, the ultimate shear strength $R_u$, $R_{u,\text{real}}$ was calculated using Eq.(1) and the yield shear strength $R_y$, $R_{y,\text{real}}$ was calculated using Eq.(2). Here, $R_u$ and $R_y$ were calculated for the nominal specified shear strength and $R_{u,\text{real}}$ and $R_{y,\text{real}}$ were for actual ones, i.e., obtained from material test of damaged clamp specimen, respectively. These shear strengths are ductile failure strengths calculated by considering the reduction in the effective cross-sectional area due to crack propagation of the upper part of the pin as shown in Fig.6.

Concerning brittle shear strength, the effects of combined stress on the pin shear strength are illustrated by several varying values of normal tensile stress of the pin ($\sigma_t$). The figure shows that brittle fracture occurs if the depth of the crack $a$ is more than the critical depth ($a_{\text{cr}}$). This alters the fracture mode from ductile to brittle. From this point onward, the apparent shear strength decreases rapidly with small crack depth increase.

Furthermore, when normal tensile force and the shear forces are both applied, the rate of reduction in apparent shear strength with respect to the crack depth becomes larger, and the shear strength decreases more rapidly with an increase in the normal tensile force on the pin.

If the normal tensile stress does not take place (as is assumed in the design), Fig.5 shows that brittle fracture will occur when the crack depth reaches the critical crack depth at $a_{cr}=0.75\text{mm}$ under the condition of $K_{II}/K_C=1$. Note that the rate of shear strength reduction increases when the assumed normal tensile stress is larger than 150MPa. This suggests that a defect with the depth of few millimeters can rapidly initiate the brittle fracture of the pin when the assumed normal tensile stress is higher than 150MPa. It is important to point out that a normal tensile stress higher than 150MPa is unlikely to occur in the loading condition, so that the probability of brittle fracture occurrence in this scenario is quite small.

On the other hand, in the case of $K_{II}/K_C = 0.7$ (Fig 6), the estimated values of fracture toughness are lower than that of $K_{II}/K_C=1$. The critical crack depth reduces to $a_{cr}=0.35\text{mm}$ and the shear strengths of the pin drop rapidly even when the assumed normal tensile stress is slightly larger than 50MPa. This suggests that when the jacking load on the hanger is the maximum limited load of 595.06kN, a small defect with crack depth of slightly over 0.5mm can rapidly initiate the brittle fracture under normal tensile stress slightly higher than 50MPa. Such normal tensile stress condition is likely to occur in the loading condition, even under controlled loading condition.
Accordingly, for both cases (Fig. 5 and 6), brittle failure could occur when the maximum jacking load creates a stress combination larger than the assumed combination of tensile and shear stresses on the pin. For the case in Fig.6, even a small tensile force can cause larger combined stresses, while in the case in Fig.5, larger tensile force is required. Therefore, the possibility of brittle fracture occurring is larger for the case in Fig 6 than it is in the case of Fig.5.

It should be mentioned that during the jacking process, the truss girder was lifted on one side. This process could have changed the inclination angle of the hanger due to geometric adjustment. As a result, there was a possibility that the jacking load acted only on one side of the pin and induced secondary lateral moment. Such secondary moment due to the lateral force of the rod might have also evoked secondary tensile stresses. This could have further increased the normal tensile stress and created an unfavorable stress condition on the pin.

Note that the results above are valid only if the following preconditions and assumptions are satisfied: 1) some crack-like defects at the base of the pin had been propagating due to repeated loading and they were not detected due to lack of maintenance, 2) normal tensile stress was not considered when designing the pin, and 3) the fracture toughness at room temperature of the pin was significantly low. These preconditions and assumptions are in line with the national investigation team report, which concluded that accumulation and combination of inadequate design, lack of maintenance and improper retrofit work have led to the bridge collapse.

5. CONCLUDING REMARKS

The present study discusses the possibility of shear brittle fracture of the pin under the loading condition in the repair work by means of linear fracture mechanics. Utilizing the information from the Charpy impact absorbed energy of the failed clamps, we estimated the fracture toughness of the high-strength ductile iron FCD-600 used for the pins and clamps. The stress condition on pins and clamps were analyzed from the fracture mechanics viewpoint by comparing the fracture toughness and the estimated actual stress on the structure. The result shows that even though the load on the hanger is lower than the maximum jacking load, a brittle fracture may occur under combined normal tensile and shear stress, when a crack-like defect exists on the base of the pin.

REFERENCES


(Received October 16, 2013)