트러스 철도교에서 피로손상이 발생한 절취된 세로보의 보강방법

Repair of Fatigue Damage of Coped Stringers in Railway Truss Bridge

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ABSTRACT : 단순 전단연결 구조를 가진 강철도교의 세로보 단부의 절취부위에서 많은 피로균열이 발견되었으며, 이러한 부위의 피로균열은 피로손상의 전형적인 예이다. 피로균열을 가진 세로보 절취부위의 보강방법을 연구하기 위하여 가로보 및 세로보의 상부 플랜지에 인장판을 부착한 경우와 부착하지 않은 경우로 구분하여 피로실험을 수행하였다. 피로실험에 사용된 하중은 현장에서 측정된 실동응력을 기초하여 빈도해석을 통해 산정하였다. 피로실험 결과, 인장판으로 보강한 모멘트 저항 연결구조상세가 철도교에서 균열성장을 효과적으로 정지시킬 수 있는 것으로 판명되었으며, 피로손상을 가진 절취부위의 보강방법으로 제시될 수 있을 것으로 사료된다.

1. INTRODUCTION

The railway bridge shown in Fig. 1, consisitng of truss and plate girder was constructed on 1983. Simple shear connections are used in both truss and plate girder, when the stringers are designed, assuming the stringers are unrestrained to rotation. Based on the simple shear connection design of stringers, the coped stringer is cut through the flanges to fit into the connection. A cope can reduce the in and out-of-plane rotational restraint of the stringer at both ends, resulting in reduction in its resistance to bending and lateral torsional buckling[1]. It is common practice to cope flanges by flame cutting which creates high tensile residual stresses. This flame cutting at the reentrant corner make the cope very susceptible to fatigue cracking. In the fabrication of the bridge shown in Fig. 1, the rectangular cope creates much higher stress concentrations at the corner of cope compared to round cut.

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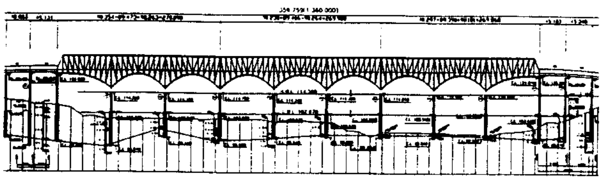


Fig. 1 Sideview of Railway Bridge

Cheng and Yura[2] investigated local web buckling behaviour of coped beams with various coping details using finite element analysis and experiments. The results showed that the stress concentration factor depends on the cope geometry and localized yielding due to stress concentration does not significantly affect the buckling capacity of coped beams. To investigate the fatigue behaviour, Yam and Cheng[3] tested full-scale specimens of coped beams with two test parameters for stress range and cope radius. They showed that the cope geometry influenced the initial stage of cracks and stress concentration and recommended that the actual stress range, which is the nominal stress range multiplied by the stress concentration factor, could be used along with category C from S-N curves in the AISC specification. Since the cope is made by flame cutting with sharp angle, the high tensile stress exists at the cope area. The existence of fatigue cracks and corrosion in the coped stringers of the highway truss bridge was reported in [4]. The stringer connection type is similar to that of the bridge of research target shown in Fig. 1. Keiji et. al. [4] investigated the behaviour of coped stringers by static test and numerical analysis. The results showed that adding cover plate on the top of flange was efficient way to repair the damaged stringer but can not be applied to the highway bridges with concrete slab due to the difficulty of construction.

The fatigue cracks nominally initiated at some form of stress concentration. This may be caused either by gross change of shape in the structure or by a local change of shape such as the bolt hole. In the recent visual inspection and dye penetration test of the railway bridge on Han River, many cracks were found at the coped ends of stringers connected with the floor beam in both the truss and the plate girder bridge[5]. The cracks tended to propagate diagonally, i.e. perpendicular to the direction of the principal stress. In order to stop the crack propagation, the stop hole was drilled at the crack tip and spliced plate was patched with high tensile bolting. In addition, supporting brackets were installed beneath the ends of stringers. The crack of stringer in the plate girder bridge was almost arrested. However, another cracks in some of the stringer in the truss bridge were occurred above the spliced plate. The first and second cracks were shown in Fig. 2. The finite element analyses of coped stringer with and without patching plate on the web of the stringer were carried out by three dimensional modeling[6]. The results showed that the stresses of the repaired area were not high, but high stress concentration was occurred in the location above repaired plate. Although, patched plate on each side of fatigue cracks in the web has been used successfully on numerous bridges, this is not sufficient to arrest cracks in truss bridge. Because, in compared with plate girders horizontal distortion was occurred due to the eccentric wheel loading and impact loading by rail ties and moment in connection was increased due to the relatively long length of the stringer whenever the subway passed the truss bridge. In other words, the simple shear connection design which is against the transverse shear force is not proper in order to reduce the high stress concentration on coped area in the truss type bridge.

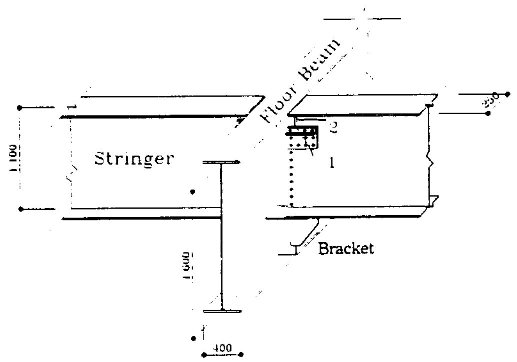


Fig. 2 Current Cracking at Coped Stringer

The main objectives of this research are to identify the cause of cracks in the coped stringers and to propose the proper repairing method which fatigue cracks can be prevented. The fatigue tests were carried out to investigate the proper connection model repairing against fatigue damage. In order to reappear the traffic loading in experiments, the service stresses measured under the random traffic loading were transformed into the variable amplitude loading and utilized in the fatigue test. The first step is fatigue test of the stringer with rectangular and round cope to see the effects of cope radius influencing on the fatigue behaviours. The rectangular coped stringer with the fatigue crack is chosen and the cover plate is added at the top of the floor beam and the stringers. Then the fatigue test of the stringer was continued to see the effects of crack development and fatigue life.

2. FATIGUE TEST

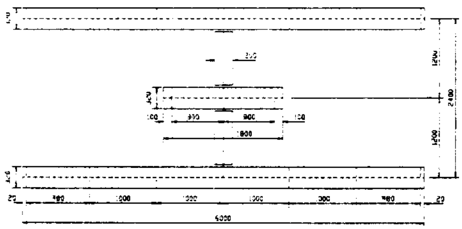
A series of fatigue tests was conducted on 7 full-scale specimens which were fabricated with approximately 7mm fillet welding and H/T (F10T M22) bolting to member connection. Continuous welding was run between the tacks to avoid cracks to be occured by any discontinuous welding. All bolts were tightened according to the provisions using torque-turn method. Specimen designations and descriptions are presented in Table 1 and dimensions of specimens are shown in Fig. 3.

Table 1. Specimen Description

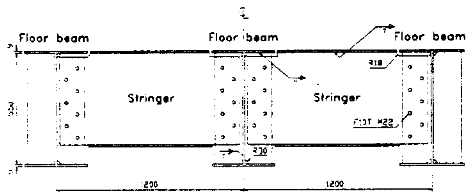
Specimen description	type of cope geometry	Stress range, $\Delta\sigma_{RMC}$(kg/cm^2)
F-A-1	Rectangular cope	972
F-A-2		666
F-A-3		927
F-A-4		863
F-B-1	Round cope	939
F-B-2		1,388
F-B-3		1,633
Remarks	F : fatigue test A : rectangular cope B : round cope	

All specimens were made of SWS 400C steel plates(minimum yielding stress : 2,500kg/cm^2, tensile strength : 4,100-5,200kg/cm^2, minimum Charpy absorbed energy at 0℃ : 4.8kg · m) and their longitudinal direction was made coincident with the rolling direction. Tensile test and Charpy V-notch impact test were conducted on SWS 400C steel plates used to fabricate the specimens. The mechanical properties of the steel plates are shown in Table 2.

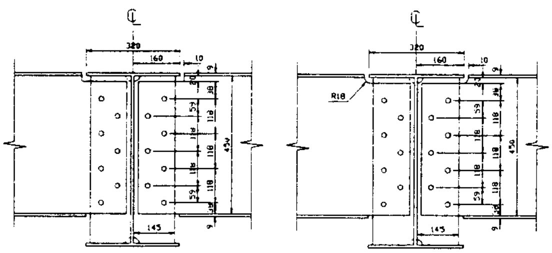
In order to decide the fatigue loading to be used in experiment, the strain cycles shown in Fig. 4(a) were measured at site under the



(a) Planview



(b) Frontview



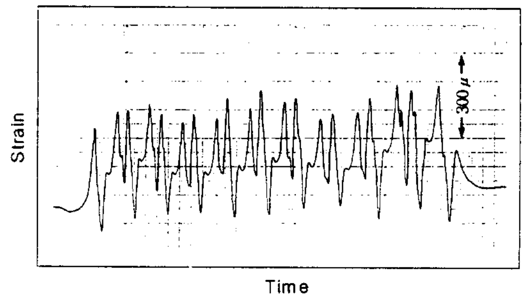
(c) Detail of Rectangular Cope (d) Detail of Round Cope

Fig. 3 Dimension of Specimen

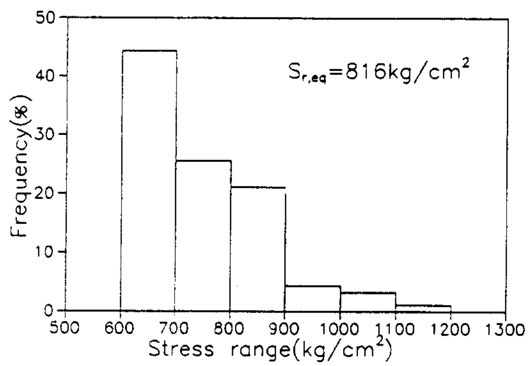
Table 2. Mechanical Properties of SWS 400C Steel Plate

Yield stress, σ_y(kg/cm^2)	Tensile strength, σ_u(kg/cm^2)	Young's modulus, E(kg/cm^2)	Elongation (%)	Charpy absorbed energy (kg·m)
3,197	4,420	2.11×10^6	31.7	6.5

random traffic loading. The strain gauge was placed 10mm from the crack tip. The cycling stresses include all traffic conditions, i.e. selfweight of vehicle, weight of passengers, inertia force, impact force, braking force and so on. Using rain flow cycle counting method[7], the measured actual stresses under random traffic loading were transformed into the stress range histogram shown in Fig. 4(b). Then, the variable amplitude block loading was controlled



(a) Example of Measured Strain Cycles



(b) Basic Stress Range Histogram

Fig. 4 Fatigue Loading

to change the equivalent stress range and applied to the specimens in fatigue test.

The 50tonf hydraulic fatigue test machine shown in Fig. 5 was used for the overall test setup. The loading and supporting points are

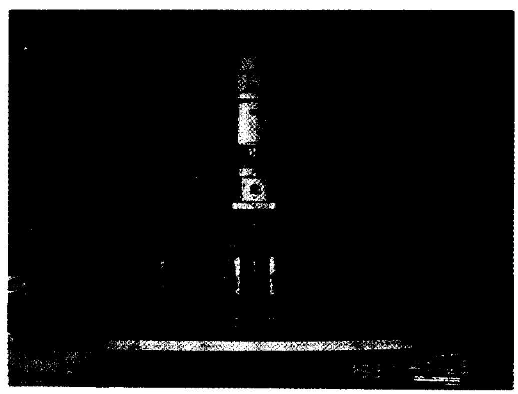


Fig. 5 Overall Test Setup

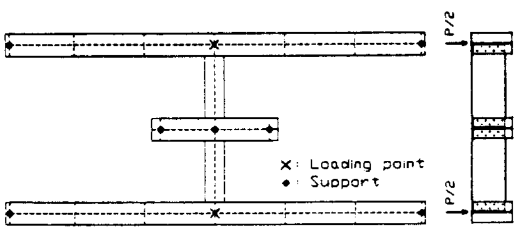


Fig. 6 Loading and Supporting Point

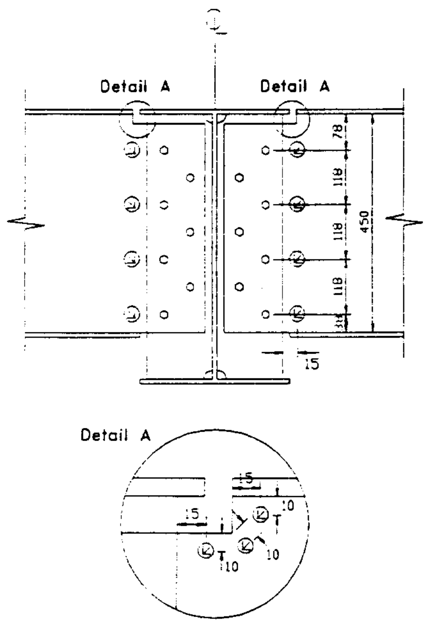


Fig. 7 Location of Strain Rosette

shown in Fig. 6. All specimens were tested with one point loading at each midspan of side floor beams. The specimens were simply supported by roller. Strain rosettes were mounted on the test specimens shown in Fig. 7.

Since high tensile residual stresses are produced by the flame cutting near the cope, premature yielding of the material in this region was expected at an early stage of loading. To redistribute the stress in the vicinity of the cope region, the specimen was statically loaded to the maximum load level to be used during the fatigue test and was then unloaded. This loading and unloading procedure dissipated the residual stresses, allowing the material in the cope region to respond elastically within the applied load range upon reloading. Strains were recorded at different static loading levels prior to fatigue test. The fatigue test was conducted at a loading frequency of 2.0 to 3.5Hz.

The locations where the development of the cracks is expected were examined by using the microscopic equipment to find out any small cracks. Crack growth data were obtained by measuring the crack length manually at convenient intervals after crack was first detected. The tests were then carried on until the maximum length of crack is 150mm and this stage is considered as a failure of test member.

3. FATIGUE TEST RESULTS

Based on physical observation of fatigue test, the fatigue process can generally be divided as two distinct phases: the life of fatigue crack initiation[N_i] and the propagation life of fatigue crack[N_p]. The size of the crack at the transition from initiation to propagation is usually unknown and often depends on the point of view of the analyst and the size of the component being analyzed. However, the distinction between the initiation life and propagation life is important. The initiation life is assumed to be the portion of life spent developing a small crack. The propagation life is the portion of the total life spent growing crack to failure. In this study, the crack initiation life is defined as time to take crack length to be 9mm which is the thickness of the

Table 3. Relation of Stress Range and Fatigue Life

Test specimen		Stress range, $\Delta\sigma_{RMC}$(kg/cm^2)	Initiation life (N_i)	Propagation life (N_p)	Fatigue life ($N_f=N_i+N_p$)
Rectangular coped stringer	F-A-1	972	75,000	412,000	487,000
	F-A-2	666	510,000	–	2,000,000*
	F-A-3	927	110,000	573,000	683,000
	F-A-4	863	100,000	694,000	794,000
Round coped stringer	F-B-1	939	876,000	–	2,000,000*
	F-B-2	1,388	503,000	362,000	865,000
	F-B-3	1,633	336,000	167,000	503,000

spectmen and the propagation life is defined as life to take crack length to be from 9mm to 150mm.

The fatigue test results are summarized in Table 3, showing fatigue lives for the different level of stress ranges and different types of cope geometry.

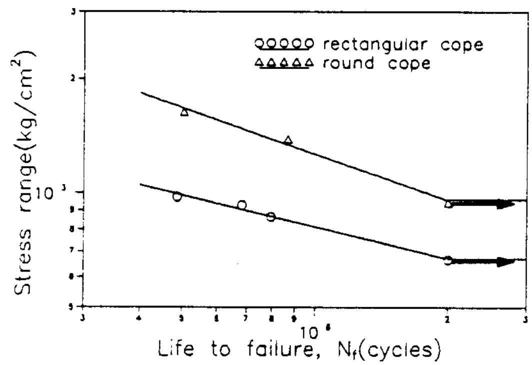


Fig. 8 S-N_f Curves

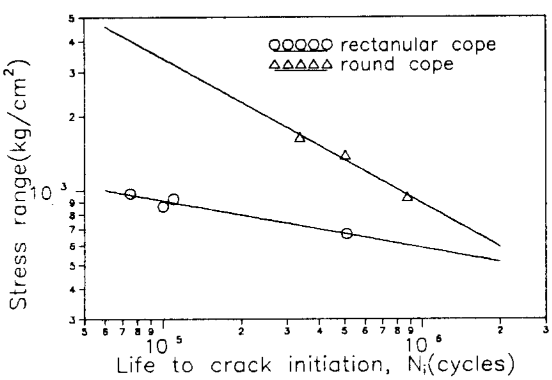


Fig. 9 S-N_i Curves

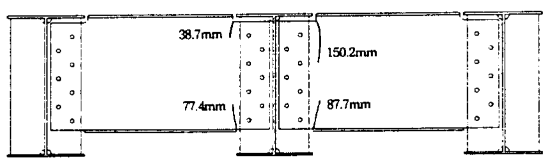
The ratio of life of initiation to fatigue life is 12.6~16.1% for the rectangular cope of stringer and 58.2~66.8% for the round cope. The cracks of the rectangular cope propagate faster than those of the round cope. Based on Table 3, the fatigue strength curves, S-N_i and S-N_f are schematically presented in Fig. 8 and Fig. 9 respectively.

For the rectangular and the round coped stringer, the fatigue strengths for 2×10^6 cycles are obtained by regression analysis as shown in Table 4. The fatigue strength of the rectangular coped stringer is 671kg/cm^2 which is about 70% of that of round coped stringer. Therefore, it can be recommended that the coping should be cut round to increase the fatigue strength.

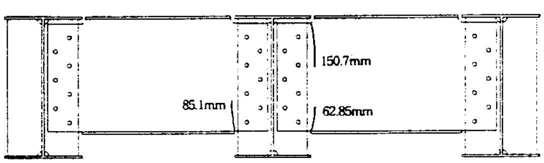
Table 4. Fatigue Strength of Rectangular and Round Coped Stringer

Type of cope geometry	Regression analysis	Fatigue strength for 2×10^6 cycles
Rectangular cope	$S = 37{,}338N^{-0.277}$	671(kg/cm^2)
Round cope	$S = 346{,}787N^{-0.406}$	959(kg/cm^2)

The crack development and the propagation of specimens classified by different type of cope geometry are investigated. As expected, the crack of rectangular cope of the stringer was initiated at the cutting corner and later on another crack caused by out-of-plane stress was begun to occur at the bottom of the web and flange. The two cracks were continued and the crack of lower part was stopped with the length of about 80mm. But the upper crack was propagated to the length of 150mm. However, the crack of round cope of the stringer was initiated at the bottom of the connection between the web and flange and later on the second crack was initiated in the round cope region. The cracks at the final stage and the crack growth curves(a-N curve) are shown in Fig. 10 and Fig. 11, respectively. As expected, Fig. 11 shows that the fatigue life of the coped stringers decreases as the nominal stress range increases. It can also be seen from these curves that the crack growth rate, i.e. the slope of the crack growth curves, increases with increasing nominal stress range, after the crack has propagated away from the stress concentration region.



(a) F-A-1



(b) F-B-2

Fig. 10 Final Stage of Crack Development

On the other hand, when the upper crack length of specimen F-A-4 is reached to 150mm, the cover plate is added at the top of the floor beam and the stringers, to make a moment resistant connection. Repairing by cover plate

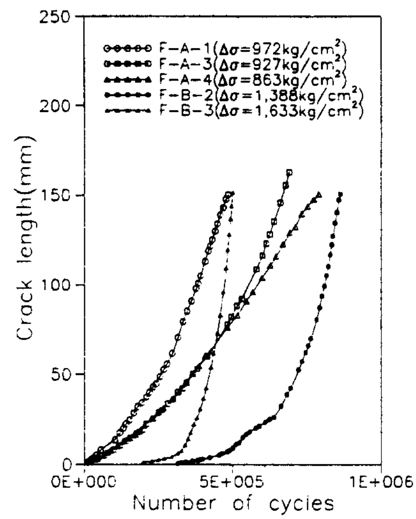


Fig. 11 Crack Growth Curves

is shown in Fig. 12. As can be seen in Fig. 13 for the crack growth rate with and without cover plate, the upper cracks were propagated to only 1mm under the 1×10^6 number of cycles and then it was stopped. The lower cracks were also almost stopped. The results of static loading condition prior to fatigue test are shown in Fig. 14 with regard to maximum

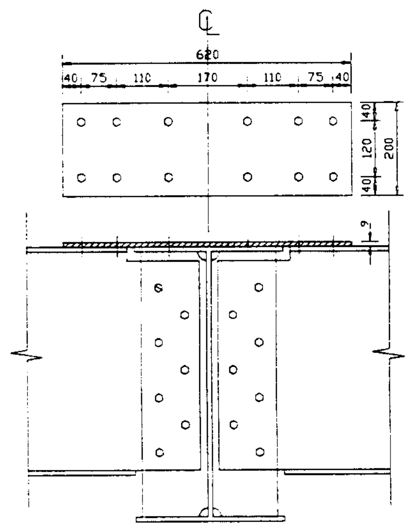


Fig. 12 Repairing by Cover Plate

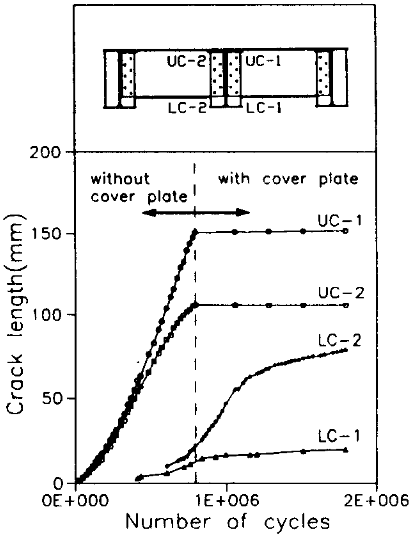
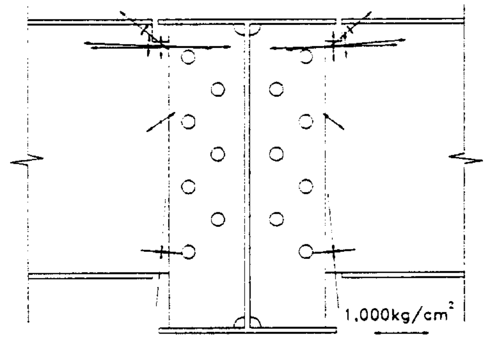
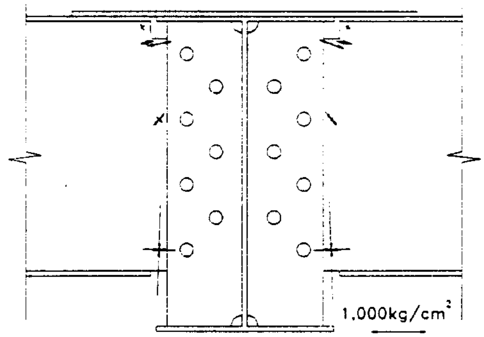


Fig. 13 Crack Growth Curves for with and without cover plate



(a) without Cover Plate



(b) with Cover Plate

Fig. 14 Maximum Principal Stresses under 15tonf

principal stresses under 15tonf. It is found that the cover plate mitigates stress concentration at cope region effectively.

Based on this test results, in order to stop the crack propagation in the coped stringer, it is very effective to make the connection between the stringers and the floor beam continuous by adding the cover plate. The top flanges of floor system in the bridge shown in Fig. 1 are coplanar, so the cover plate connection shown in Fig. 15 can be recommended for repairing method. The floor beam and the stringers are connected with sufficient rigidity to transfer the moments with little rotation of stringers relative to each other. The flange of stringers can be considered to carry all the moment and the web only the shear.

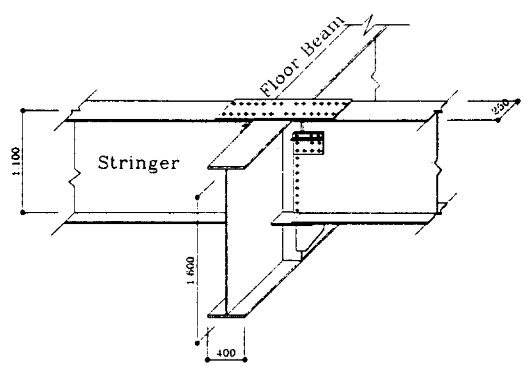


Fig. 15 Recommended Connection Detail for Floor System

For the parametric study of the connections with and without moment transfer, a finite element analysis is being carried out by three dimensional model. The results of the parametric study will be published in the next paper.

4. CONCLUDING REMARKS

In the railway truss bridge with high stress range under traffic, many cracks were discovered in the coped stringers repaired with patching plate subjected to fatigue loading. From the results of field inspections, the repairing method which patches the plate in the web of stringer and supports the bracket is proper in the plate girder bridges but not in railway truss bridge. To investigate the repairing method of the coped stringer with the fatigue damage, fatigue test was carried out. The results of fatigue test show that the moment resistant connection is an efficient way and recommended as the repair design concept of fatigue damaged stringer in railway truss bridge.

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