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ROBUSTNESS EVALUATION OF DOUBLE DIAGONAL TEN PANEL THREE SPAN CONTINUOUS AIR-RAID PROOF BRIDGE

Mya San WAI[1] and Yoshikazu TAKAHASHI[2]

[1]Student Member of JSCE, Student, Dept. of Civil and Earth Resources Eng., Kyoto University
(Kyoto Daigaku Katsura, Nishikyo-ku, Kyoto, 615-8540, Japan)
E-mail: myasanwai@gmail.com
[2]Member of JSCE, Professor, Dept. of Civil and Earth Resources Eng., Kyoto University
(Kyoto Daigaku Katsura, Nishikyo-ku, Kyoto, 615-8540, Japan)
E-mail: takahashi.yoshikazu.4v@kyoto-u.ac.jp

The robustness evaluation and development of robust structure for the air-raid proof bridge are presented. The effect of damage of structural components on the performance of the bombing resistant double diagonal ten panel three span continuous truss bridge with regarded to the different robustness indices of structure are inspected by conducting linear static analysis using OpenSees software. The damage of internal indeterminacy and the damage of external indeterminacy are considered for enhancing the bombing resistant redundant robust structure. The new idea of influence lines are proposed in the evaluation of the robustness of the structure and the critical components are found out. In addition, the behavior of air-raid proof bridge for the intact and damage conditions are determined by means of damage influence lines of stresses and the real acting stresses of the detected members. The practices of improving robust structure are proposed by adding the suspension truss structure to the existing double diagonal ten panel three span continuous truss bridge and by increasing cross sections of the affected members based on the damage of critical parts of structure. In relating with the structural strengthening on the damage condition of structure, the traffic control technology from the structural engineering point of view are suggested. In order to improve the bombing resistant high redundant robust structure, the combination of different countermeasures of internal indeterminacy, external indeterminacy, suspension truss structure and estimation of cross sections of members are recommended.

Key Words : *air-raid proof and robust structure, internal and external indeterminacy, damage influence lines, structural strengthening, traffic control*

1. INTRODUCTION

The bombing resistant bridges were becoming developed since the World War times. The double diagonal truss bridges were developed and constructed in the Korean Peninsula at the end of World War II as the bombing resistant structures. The double diagonal single span truss bridges and the double diagonal continuous span truss bridges were proposed as the design standard models for the purpose of locomotive trains at that time[1]. In this study, the bombing resistant double diagonal ten panel three span continuous truss bridge is adopted to demonstrate the practice of enhancing the robust bombing resistant structure. The damage of internal indeterminacy and the damage of external indeterminacy are considered for enhancing the bombing resistant robust redundant structure. The practice of enhancing robust structure is verified by adding the third countermeasure suspension truss structure to the existing second countermeasure of double diagonal ten panel three span continuous truss bridge and by increasing cross sections of the affected members based on the damage of critical parts of structure.

The most critical component of the structure is found out using three robustness indices such as the conditioning of stiffness matrix, period of structure and displacement which characterized the linear elastic behavior of the structure that are related to the elastic stiffness and first yielding. The robustness of structure based on the damage of internal indeterminacy (damage of one member) and the damage of external indeterminacy (damage of one bearing support) are expressed using the influence lines which are different from the conventional influence lines. The damage structures are related with the nonlinear behavior. However, in this study the damage of whole member is considered in the linear elastic behavior of structure. The influence lines are primarily used to determine the critical position of the moving live load in the bridge engineering. The calculation of the influence line is based on the linear elastic behavior of the structure, it can only be directly used to identify the most critical load position which will cause the most critical component to reach its elastic limit[2]. The influence lines are not related with the earthquake bridge engineering. In this study, the influence lines are proposed for the robustness evaluation and development of robust structures in terms of robustness indices and in terms of stresses. F. Biodini and S. Restelli, 2008 investigated the robustness of structure using the performance indicators under linear elastic behavior[3]. Powell, 2009 proved that the assumption of linear behavior can be successfully used in design of robust structures[4]. In order to use the linear characteristic robustness indices and the influence lines that are related with the linear elastic behavior of structure, the linear static numerical analysis of the adopted structure is conducted by using OpenSees software[5]. The linear analysis is applicable the structural problem in which the stresses remain in the linear elastic range of the material. In linear analysis, the material properties are simplified. The relationship between the load and displacement are linear and the stiffness matrix of the model is constant and as a result, the solving process for calculation is relatively short compared to a nonlinear analysis on the same model[6].

To develop the robust structures, the behavior of structure are also conducted using the damage influence lines of primary and secondary stresses of the intact and damage structures based on the damage of critical components obtained from the robustness evaluation of three indices of structure. Then, the real acting stresses of the intact and damage structures are calculated from the influence lines and compared with the allowable stresses for the decision in the development process. The development of robust bombing resistant structure is proposed by increasing cross sections of the affected members based on the damage of critical components of structure. Furthermore, the existing three span truss bridge cannot support the full live load and no sufficient details are existent. Therefore, the existing three span continuous truss structure is developed to improve the robustness of structure and to support the full live load of locomotive train by adding the suspension truss structure and by estimating the cross section of the truss members. In relating with the structural strengthening of the damage structure, the traffic control technology from structural engineering point of view are also presented.

2. HISTORY OF DOUBLE DIAGONAL CONTINUOUS TRUSS BRIDGES

The double diagonal continuous truss bridges were constructured in the Korea Peninsula by Railway Bureau of the Government-General of Chosen as the bombing resistant high redundant structures for the railway bridges during the end of the World War II. One of the bridges is Imjin river bridge located at about 40 km north of Seoul and built in 1939. It was a double diagonal eight panel continuous truss bridge and as in **Fig.1**. It was bombed during the Korean War, and the upper level bridge was completely destroyed. Another bridge is the Yalu river bridge which is a friendship bridge between China and North Korea as in **Fig.2**. It was constructed by the Imperial Japanese Army between 1937 and 1943. During the Korean War, the United States Air Force repeatedly bombed the Yalu River bridges. The Japanese researcher Dr. Oda (1941) conducted the linear gravity hand calculation analysis for the different types of double diagonal truss bridges to check the behavior of structures in the doctoral dissertation[1]. In this study, double diagonal ten panel three span continuous truss bridge is selected as a case study to develop the robust redundant structure. All the structural form, dimension and material properties are collected from the reference of Dr. Oda's dissertation. From the reference, the cross sectional area, moment of inertia and center of depth of the members are available. The detailed cross of the members of truss cannot be obtained. The structural form of double diagonal ten panel three span continuous truss bridge is shown in **Fig.3**. The truss members are identified as O1 to O30 for top chord members, U1 to U30 for bottom chord members, D1 to D30 for the left inclined

Fig.1 Present Imjin river bridge[1].

Fig.2 Present Yalu river bridge[1] .

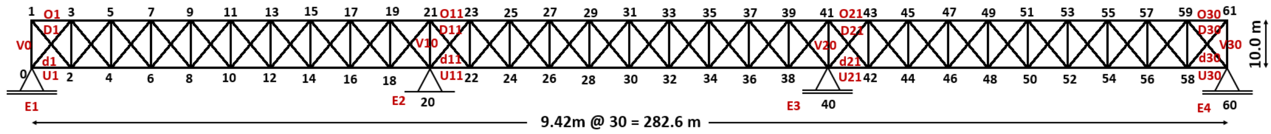


Fig.3 Double diagonal ten panel three span continuous truss bridge.

diagonal members, d1 to d30 for the right inclined vertical members and E1 to E4 for bearing supports respectively. The critical components of three span continuous truss bridge are detected based on the damage of the internal indeterminacy and external indeterminacy in terms of the linear elastic characteristics three robustness indices by using the influence lines. The structural strengthening and traffic control technology are presented. To support the dead load for the damage structure, the strengthening is conducted by increasing the cross sections of the directly affected members based on the damage of critical components of bridge to develop the robustness of structure. To support the full live load for intact structure, the improvement includes not only the addition of the suspension truss structure to the existing bridge but also the estimation of cross section of members that will support for the ordinary design purpose.

3. STRUCTURAL ROBUSTNESS

The concept of robust structures is becoming more common in engineering profession practice for the reliable structures. Robustness is defined as the ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause[7]. The robust structures can prevent the excessive failures from the loss of the critical components of structures by the alternative load paths. Various researchers developed the different forms of robustness indices for the evaluation of robustness of structures such as risk-based measures, probabilistic measures and deterministic measures.

S. Restelli, 2007 investigated several deterministic performance indicators that are associated with the serviceability conditions under elastic behaviors such as the elastic stiffness and the first yielding for the evaluation of the robustness of structures. Powell, 2009 pointed out the applicability of the robust structure design for linear behavior[4]. F. Biodini and S. Restelli, 2008 proposed the performance indicators relating to the properties of the structural system and the loading conditions[3]. The performance indicators relating to the structural properties and loading condition are as follows

$$c = \frac{\max_i \lambda_i(K)}{\min_i \lambda_i(K)} \tag{1}$$

$$T = 2\pi\sqrt{\max_i \lambda_i(K^{-1}M)} \tag{2}$$

$$s = \|s\| = \|K^{-1}f\| \tag{3}$$

where c is the conditioning number of the stiffness matrix K and T is the first vibration period associated with the mass matrix M and $\lambda_i(K)$ denotes the i^{th} eigenvalue of the matrix K and s is the displacement vector, f is the applied load vector and $\|\,.\,\|$ denotes the euclidean scalar norm[3]. The two indicators associated with the conditioning of the stiffness matrix and the vibration period are related to the properties of the structural system only. The displacement indicator is related to both the system properties and the loading conditions. The behavior of the structure may differ depending on the different structural systems and the different loading conditions[3].

The dimensionless robustness indices related with the performance indicators investigated by F. Biodini and S. Restelli, 2008 are expressed as follows

$$\rho_c = \frac{c_0}{c_1} \tag{4}$$

$$\rho_T = \frac{T_0}{T_1} \tag{5}$$

$$\rho_s = \frac{s_0}{s_1} \tag{6}$$

where the scripts '0' refers to the original intact state and '1' refers to the damage state of the system. ρ_c refers to the robustness index for the conditioning of the stiffness matrix of the structure, ρ_T refers to the index for the period of the structure and ρ_s refers to the index for the displacement of the structure.

The three robustness indices have the advantages of simplicity and easy to calculate and each index reflects the significant characteristics on the behavior of the structure[8]. The stiffness matrix is an inherent property and represents the static characteristics of the structure and encloses the geometric and material behavior information that indicates the resistance of the element to deformation when subjected to loading. Condition number reveals the sensitivity of "something" with respect to the change of data, in this case the perturbations of the stiffness matrix. Conditioning number of stiffness matrix is used to measure the sensitivity of the structural properties of the system. The natural period of vibration is an important dynamic factor which defines how a structure will have the response to a severe ground motions[9]. The period of vibration is related with mass, stiffness and strength and consequently on all factors which affect characteristics such as structural material and type, dimensions and section properties[10]. Displacement represents the static characteristic of structure that dedicates the deformation of the structural system and indicates as the representatives for the limit of the acceptable measures of the system failure.

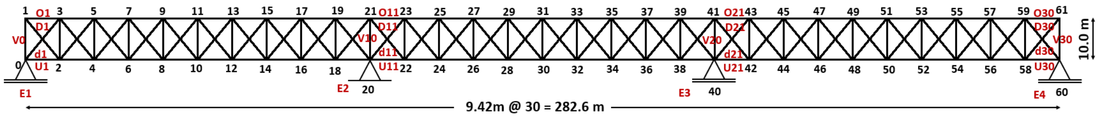
The three indices are adopted to predict the behavior of structure under the damage condition of internal indeterminacy and external indeterminacy. The most critical components of structure are identified.

In the eigen analysis, the numbers of eigen values of the structure are equal to the numbers of degree of freedom (DOF) of structure. In the 2D model of target structure, there are total of 181 DOF (62×3 - (1×3 + 2×1) = 181) for intact structure case. The numbers of DOF will be reduced for the damage structure case. The members of the truss are connected at the respective nodes in the model. Every node at the connection of the members has 3 DOF except the support points. Each DOF belongs to the corresponding stiffness and mass of the structure. According to the numbers of degree of freedom (DOF), the minimum and maximum of the eigen value can be obtained. For the analysis of the target model, the mass of the truss members are assigned at the respective nodes. In case of the stiffness of structure, the material properties are identified using the Young modulus E and the linear elastic commands are used for the material behavior. The required period and the eigen values of stiffness matrix are obtained directly from the eigen analysis of the target model and the displacement of structure is obtained from the gravity analysis of structure. Then, the robustness indices are calculated. For the stiffness matrix of structure, ‘standard’ eigen command is used in OpenSees as only the stiffness identified in the robustness index and no relation with the mass matrix of structure. For the period of structure, ‘general’ eigen command is used since the period of structure in the robustness index includes both stiffness and mass of structure. In equations (1) and (2), the definition of the stiffness matrix and period of structure are explained and how the stiffness matrix and the period of structure identified in relation with the mass matrix are presented.

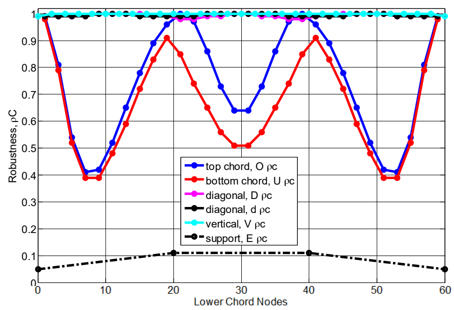
As the review from the study of whole process, it can be deduced that the results from the three robustness indices and the results from the influence lines of intact and damage structures and its real acting stresses give the consistent results for the evaluation of robustness and development of robust structure.

4. DETECTION OF CRITICAL COMPONENT BY ROBUSTNESS INDICES

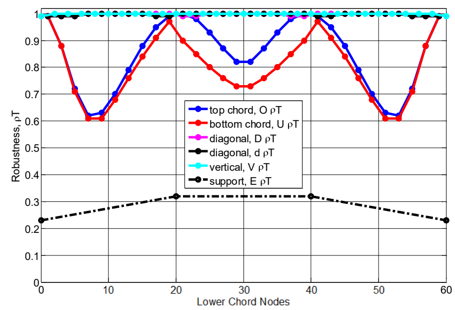
The new idea of influence lines are proposed for the robustness evaluation. The influence lines are



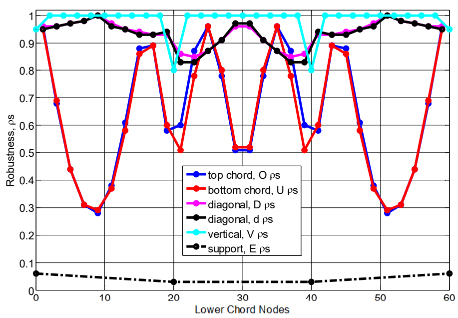
(a) Double diagonal ten panel three span continuous truss bridge



(b) Robustness for conditioning of stiffness matrix



(b) Robustness for period



(d) Robustness for displacement

Fig.4 Robustness ind ices of ten panel three span continuous truss bridge for damage of one member and external support.

attractive for the illustration of the damage member location and its influence on the structure performance.

The damage of the components of the structure are considered as the internally indeterminacy and the externally indeterminacy of the structure as well. The totally damage of structural component is considered and the entire component is removed to identify the damage of structure. The performance of double diagonal three span continuous truss bridge is assessed in terms of the robustness indices of the structure with respect to the damage of one member and external support using the influence lines. The three robustness indices, the conditioning of stiffness matrix, the period of structure and displacement of structure are related to the linear elastic stiffness of structure and the first yielding. The self-weight of the truss members are considered as the dead load and applied at every node of the respective members. The influence lines of one damage member and external support for three robustness indices of ten panel three span continuous truss are shown in **Fig.4**.

The tendency of the robustness indices of the conditioning of the stiffness matrix of structure and period of structure have the similar and but the displacement robustness index has different tendency with two indices. According to three robustness indices, the damage of the top chords and the bottom chords are the most effective members to cause the failure of the structure.

When the damage of the member may cause the failure of whole structure, it says that the member carry much capacity to support the whole structure, known as “the critical member”. The top chords and the bottom chords at the center of three spans are the critical members since the robustness indices are the smallest in the damage of those members and the robustness values become larger from the center of the span towards the supports for all three spans. This is due to the fact that the cross sections of the members become larger from the supports towards the center of the spans. The robustness indices of the conditioning of the stiffness matrix and the displacement of structure are more influence than the robustness index of period of structure to cause the system collapse. The robustness indices of the conditioning of the stiffness matrix and the displacement of structure vary from low to high robustness depending on the location of the members. The period index varies from intermediate to high robustness values.

The diagonal members and the vertical members show the high robustness for all three indices along three span truss and have the small effect to the system strength and these members convey only small quantity of strength. The indices of the conditioning of stiffness matrix and the period of structure are almost ‘1’ and the displacement index varies from ‘0.82 to 1’ along three span length. In compared with the damage of one member in the single span truss bridge, the effect of damage of one member in the three span continuous truss bridge is smaller than the single span truss bridge due to the effect of the continuous system[8)]. The damage of external bearings have more impact than the damage of the internal members. The damage of the support bearings have great effect to the failure of the whole bridge. Even the damage of one external support may cause the totally failure of the structure. It can be said that the damage of the external bearing is the largest influence to the collapse of the bridge.

The damage of exterior support E1 or E4 is more influence than the damage of the interior support E2 or E3. The outermost two supports E1 and E4 have similar effect to support the system strength, and more influence than the supports E2 and E3. The interior supports E2 and E3 also have the similar effect to support the system stability or to cause the failure of the structure.

5. DAMAGE INFLUENCE LINES OF STRUCTURE

The influence lines are primarily used to determine the critical positions for placing live loads in the bridge design. The calculation of the influence line is based on the linear elastic behavior of the structure. The influence lines are not related with the analysis of the earthquake bridge engineering[8)]. However, in this study, the influence lines are proposed and used to inspect the behavior of structure for the robustness evaluation with the expression of robustness indices. Moreover, the influence lines of stresses are used for the intact and damage structures known as “damage influence lines” for the illustration of effect of damage component and for the calculation of the real acting stresses of the of the intact and damage structures. The behavior of structure are identified using the damage influence lines of stresses for the intact and damage structures. The term “damage influence lines” refers especially for the damage structure. The uses of influence lines are emphasized for the evaluation and development of robustness of structure in terms of the robustness indices of structures and in terms of the primary and secondary stresses of intact and damage structures. The damage influence lines are proposed for the evaluation of robustness of structures.

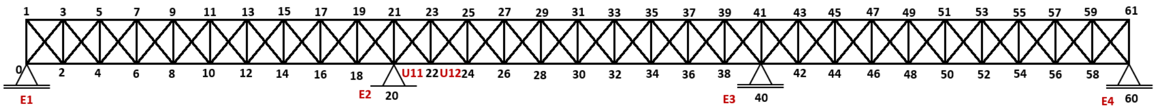
6. EFFECT OF DAMAGE OF CRITICAL COMPONENTS ON STRUCTURAL BEHAVIOR

(1) Influence lines of damage structure

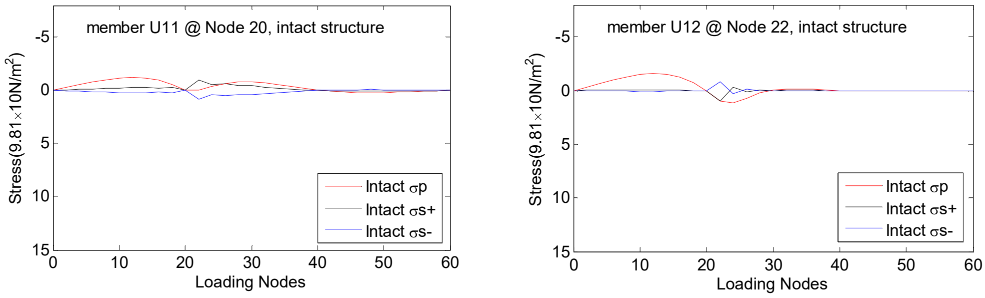
The effect of damage of critical components on the behavior of ten panel three span continuous truss bridge are inspected by using the damage influence lines of the most affected members of the intact and damage structures in terms of primary stress (σ_p) and secondary stress (σ_s). In three span continuous truss bridge, the damage of the external support is the largest influence to cause totally collapse of the bridge according to the robustness evaluation of the bridge.

Among four supports, E2 is selected first to be considered as the damage component of structure to explore the behavior of structure as the effect of the damage of the interior support. In case of the damage of E2, the behavior of the most influential and affected members for the intact and damage cases are presented. The damage influence lines of the members U11 and U12 for the intact structure are shown in **Fig.5** and for the damage structure are shown in **Fig.6**. The maximum primary stresses in two members for the damage condition change from negative maximum to positive maximum and the magnitudes are larger 4.20 times for U11 and 4.52 times for U12. The maximum secondary stresses are not apparently different for both cases and 3.01 times smaller for U11 and 1.48 times larger for U12 in the damage structure than the intact structure.

The effect of the damage of the external support E1 is also inspected to observe the behavior of the damage structure. In case of the damage of the support E1, the most influential members are O9, O10, U8 and U9 respectively. The behavior of the member O9 and O10 are presented. The damage influence lines of the members O9 and O10 for the intact structure are shown in **Fig.7** and for the damage structure are shown in **Fig.8**. The maximum primary stresses in O9 and O10 for damage structure increase drastically about 10.62 times. The difference in secondary stresses is not obviously large and 7.15 times larger in O9 and 5.24 times larger in O10 for damage structure but the magnitudes are small. Compared the

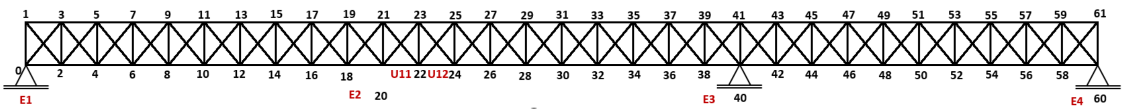


(a) Intact structure of double diagonal ten panel three span continuous truss bridge

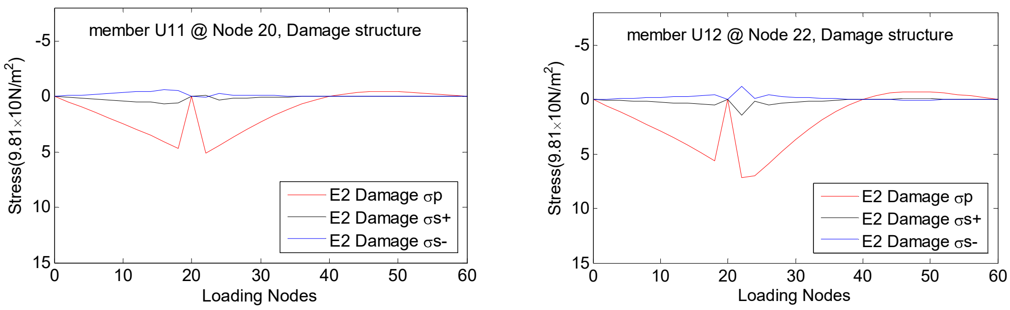


(b) Influence lines of intact structure for members U11 and U12

Fig.5 Influence lines of intact structure for members U11 and U12 in ten panel three span continuous truss bridge.

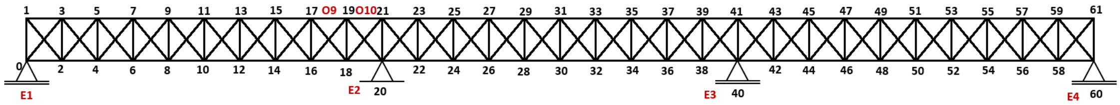


(a) Damage structure (E2 damage) of double diagonal ten panel three span continuous truss bridge

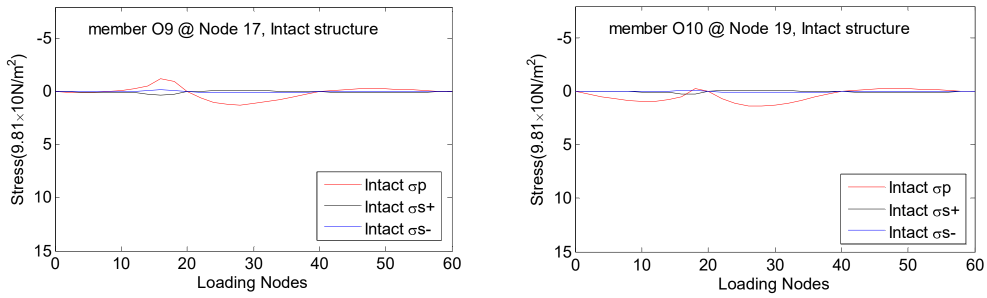


(b) Influence lines of damage structure for members U11 and U12

Fig.6 Influence lines of damage structure (E2 damage) for members U11 and U12 in ten panel three span continuous truss bridge.

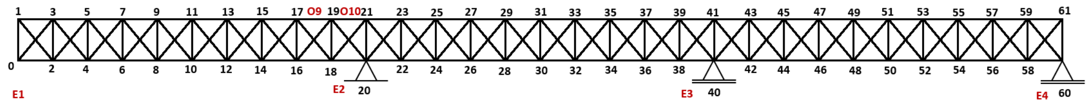


(a) Intact structure of double diagonal ten panel three span continuous truss bridge

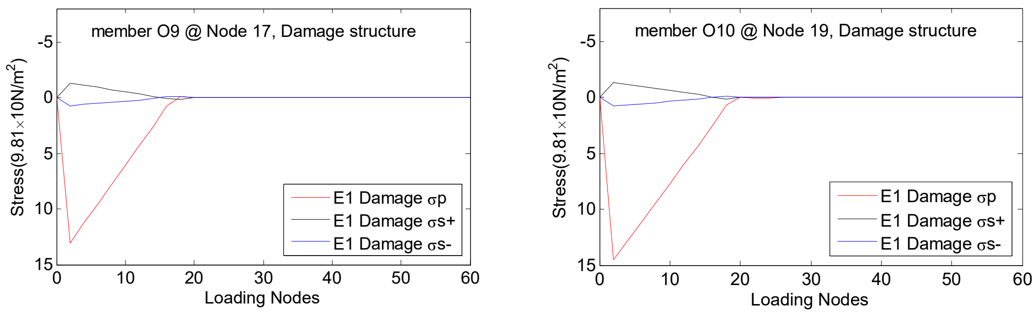


(b) Influence lines of intact structure for members O9 and O10

Fig.7 Influence lines of intact structure for members O9 and O10 in ten panel three span continuous truss bridge.



(a) Damage structure (E1 damage) of double diagonal ten panel three span three continuous truss bridge



(b) Influence lines of damage structure (E1 damage) for members O9 and O10

Fig.8 Influence lines of damage structure (E1 damage) for members O9 and O10 in ten panel three span continuous truss bridge.

damage of E1 with the damage of E2, the damage of E1 is more severe to the structural collapse and the larger numbers of failed members are occurred.

(2) Real acting stresses for damage structure

The real acting stresses of the members are calculated by the product of the load intensity and the area under the influence lines. For the dead load, the net area is considered since the dead load is fixed along the span length. For the live load, the positive and negative area are considered separately. The maximum forces are calculated from the summation of dead load plus positive live load and dead load plus negative live load respectively. The dead load and the train live load are considered for the calculation. The dead load is given as 2.45×10^6 N/m^2 and the live load is 7.36×10^6 N/m^2.

The allowable tensile strength of the steel is given as 117.68×10^6 N/m^2. The allowable compressive stresses for O9, O10 and U11 is -112.68×10^6 N/m^2 and for U12 is -112.87×10^6 N/m^2. The real acting stresses of members O9, O10, U11 and U12 for the

Table 1 Real acting stresses of the intact and damage structures of three span truss (10^6 N/m^2).

Structure / Load Case	Intact (Origin)	Damage E2 (Origin)	Intact (Origin)	Damage E1 (Origin)
	Member U11 (node 20)		**Member O9 (node 17)**	
D.L	-27.67	99.24	7.18	123.04
L.L (+ve)	41.16	343.05	60.52	404.22
L.L (-ve)	-124.17 (68.40% L.L)	-45.34	-38.97	-35.09
DL + L.L	13.49	442.28	67.71	527.27
D.L – L.L	-151.83	53.90	-31.79	87.95
	Member U12 (node 22)		**Member O10 (node 19)**	
D.L	-16.23	133.76	26.01	155.13
L.L (+ve)	30.52	463.75	97.68	502.57
L.L (-ve)	-79.21	-62.47	-19.65	-37.17
DL + L.L	14.29	597.51	123.69 (95.16% L.L)	657.70
D.L – L.L	-95.44	71.29	6.35	117.96

intact and damage structures cases are calculated to check the behavior of structures and shown in **Table 1**. The strength of the members exceeds the respective allowable values for the dead load only condition in case of the damage of the exterior support E1or E2. The members O10 and U11 cannot support the full live load even the original intact structure case. The maximum total live load can support 68.40% according to the acting stresses of member U11 for the original intact structure case.

7. IMPROVEMENT FOR ROBUST STRUCTURE

(1) Strengthening to resist dead load

According to the robustness evaluation and the real acting stresses of the considered members, the damage of the external bearing is more severe than the damage of the single member to cause the collapse of structure. The damage of the external bearing E1 is the most influential and causes the collapse of the structure for the dead load only case and the dead load plus live load case. Based on the damage of the most critical bearing E1, the method to improve the damage structure to support the dead load is proposed.

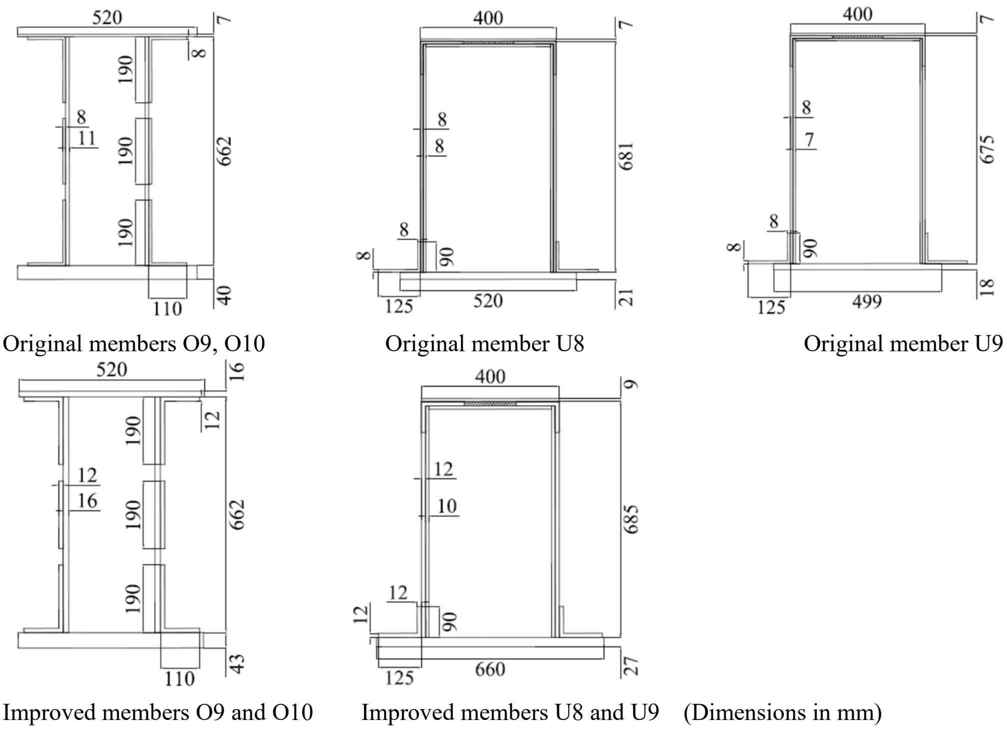
The first strategy is to support the dead load and the affected members in three panels adjacent to the supports are strengthened by increasing the cross sections of the members. The cross section of the top chord members O9, O10 and the bottom chord members U8 and U9 are increased to the member size of O6 which is 1.89 times of the member U9. For the purpose of the symmetric and consistent of the structural system of the whole bridge, the corresponding symmetric members in the three spans are strengthened. The estimated cross sections of the original members and the improved members are shown in **Fig.9**. The detailed cross sections of the members are estimated based on the existing cross sectional area, moment of inertia and the center depth of the members and its function requirements on the structure.

a) Influence lines of improved structure

The stress influence lines of the members O10 for E1 damage case and U12 for E2 damage case are checked to review the effectiveness of the strengthening and shown in **Fig.10**. The primary stresses of the improved members of the damage structure are reduced to 30% - 50% of the original damage structure.

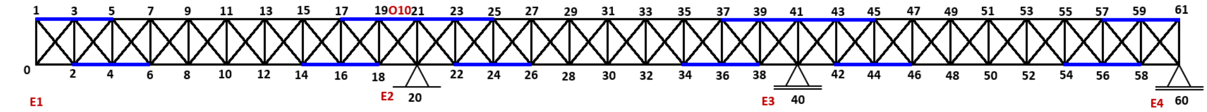
b) Real acting stresses for improved structure

The real acting stresses of the improved members O10 of the damage structures (E1 damage) and U12 (E2 damage) for the real applied dead load and live load are calculated and shown in **Table 2**. After improving the affected members by increasing the cross section of the affected members into 1.89 times of the member U9, the strengthened damage structure can withstand the dead load and however, the live load cannot be allowed according to the strength of member O10. This improvement is effective to support the dead load and suggested as the first proposal of strengthening for the case of the damage of the external bearing. The strengthening based on the damage

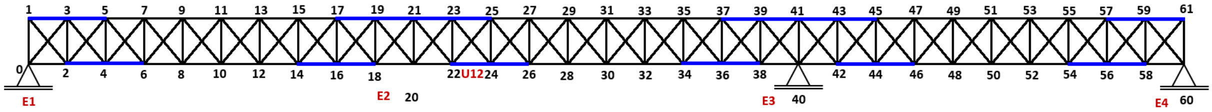


Improved members O9 and O10 Improved members U8 and U9 (Dimensions in mm)

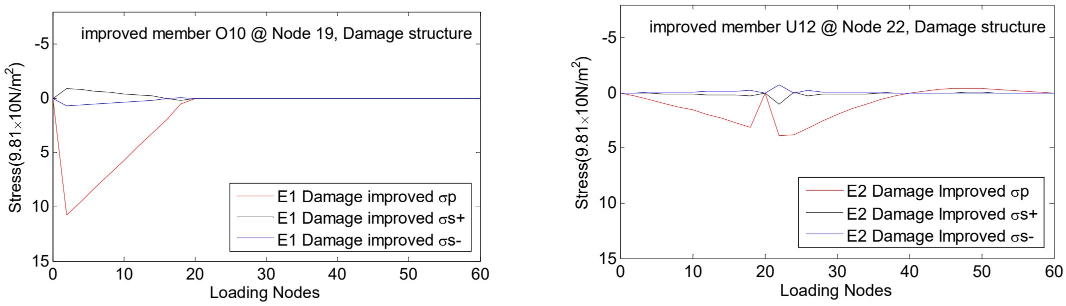
Fig.9 Estimated cross sections of original and improved members to resist dead load for damage structure (E1 damage).



(a) Improved damage structure (E1 damage) of double diagonal ten panel three span continuous truss bridge



(b) Improved damage structure (E2 damage) of double diagonal ten panel three span continuous truss bridge



(c) Influence lines of improved damage structure for members O10 (E1 damage) and U12 (E2 damage)

Fig.10 Influence lines of improved damage structure for members O10 and U12 in ten panel three span continuous truss bridge.

Table 2 Real acting stresses of the improved damage structure to resist dead load (10^6 N/m²).

Structure / Load Case	Damage E1 (Improved) Member O10 (node 19)	Damage E2 (Improved) Member U12 (node 22)
D.L	116.12	72.66
L.L (+ve)	376.20 (0.42% L.L)	251.37 (17.91% L.L)
L.L (-ve)	-27.85	-33.38
DL + L.L	492.32	324.03
D.L – L.L	88.27	39.28

of exterior bearing E1 also covers the damage of interior bearing E2 to support the dead load. The improvement is beneficial to prevent the collapse of structure under dead load in case of the damage of critical components and for the enhancement of the robust structure for the existing three span continuous truss bridge.

8. ADDING OF THIRD COUNTERMEASURE SUSPENSION TRUSS STRUCTURE AND ESTIMATING OF CROSS SECTIONS OF MEMBERS

The original intact structure of the double diagonal ten panel three span bridge cannot support the full live load. The real acting stresses of some members are larger than the allowable stresses and only the limited amount of traffic load can be permitted. The development of structure to support the full live load includes not only addition of third countermeasure suspension structure but also estimation of cross sections of members.

The first countermeasure to create the bombing resistant robust structure for truss bridge is the establishment of high order internal indeterminacy or external indeterminate redundant system. The double diagonal truss bridges include that kind of structural systems and the numbers of the indeterminacy provide to be robust structures for bombing resistance performance. In case of damage of some members or components of structure, the other members can share and distribute the load due to the high order indeterminate redundant structures. The second countermeasure to make the robust structure is the combination of the increase of the internal indeterminacy and the external indeterminacy of the system. The three span continuous truss system bridges are more robust than the single span truss system bridges. The continuous system and the bearing supports are one method for the assistance to improve the robust structure. The third countermeasure to be robust structure is the combination of three or more methods of internal and external development of indeterminacy. Double diagonal ten panel three span continuous truss bridge is a type of the combination of the internal and external reinforcement to improve the robust structure. In order to further develop three span continuous truss system, the third hanger suspension truss structure are added for the development of the bombing resistant robust structure to avoid the failure of structure when some structural components are lost[1]. To enhance the robust structure, the bombing resistant double diagonal ten panel three span continuous truss bridge referenced from the doctoral dissertation of Japanese researcher Dr. Oda (1941) is adopted and, the third countermeasure suspension truss structure are added to the upper part of the bridge to reinforce the entire truss girder. The structural form of double diagonal ten span continuous truss bridge to be considered is same as the Yalu river bridge which connects the cities of Dandong in China and Sinuiju of North Korea via railway.

(1) Yalu river bridge

The Yalu river bridge is the Sino-Korean Friendship Bridge or China-North Korea Friendship Bridge across the Yalu River on the China-North Korea border. There is both a railway and a roadway on the Sino-Korean Friendship Bridge, but pedestrians are not allowed to access the bridge. The bridge is total length of 943.3m long consisting of four numbers of double diagonal ten panel three span continuous truss bridge. In the first and second truss series, the upper parts of two numbers of three span continuous truss are hanging with suspension truss which are steel structural members. The purpose is to enhance the safety against the leakage of the components of the truss bridge. It is also expected to develop the robustness when the structure is experienced some components failure and bombing resistant capacity of structure. The whole shape looks like a suspension bridge, but it is a truss bridge, and suspended truss structure. The longitudinal profile is shown in **Fig.11**. Prior to the Korean War two bridges, about 60 meters apart, spanned the Yalu River in Sinuiju. The first bridge (now half bridge or, as it is referred to, the Broken Bridge) was built between 1909 and 1911 and had a central opening span to allow for the passage of tall ships. The second, and still operating, Sino-Korean Friendship Bridge was built by the Imperial Japanese Army between 1937 and 1943 towards the end of its occupation of Korea (1945). During the Korean War (1951-1953) both bridges were repeatedly bombed by US aircraft in an attempt to stop Chinese supplies getting through to the North Korea[11].

(2) Proposed sections for suspension truss and cross sections of members

The proposed double diagonal ten panel three span continuous truss bridge with hanging suspension truss structure is shown in **Fig.12**. The height of the tower for the suspension truss structure is estimated based on the ratio of height of the tower post of the suspension structure to the truss of the Yalu

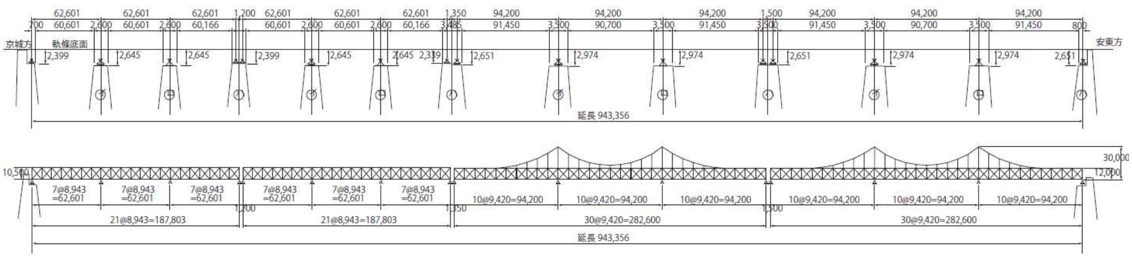
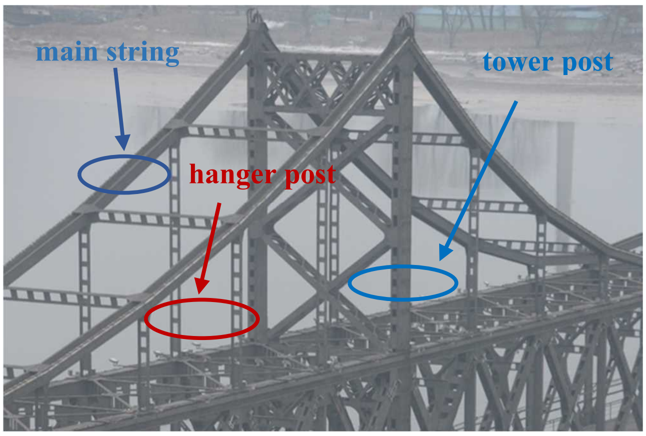
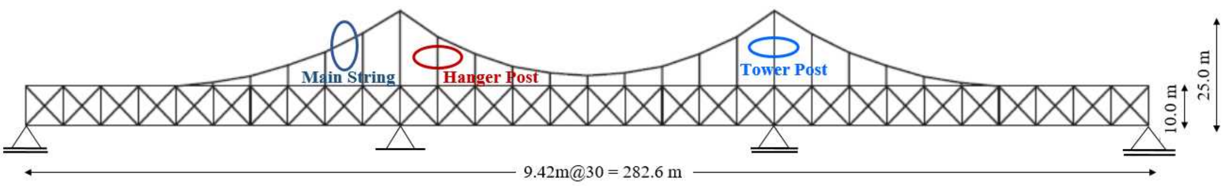


Fig.11 Longitudinal profile of Yalu river bridge[1)].



(a) Suspension structure of Yalu river bridge (Photo taken by Prof. Y. Takahashi)



(b) Longitudinal profile for proposed bridge

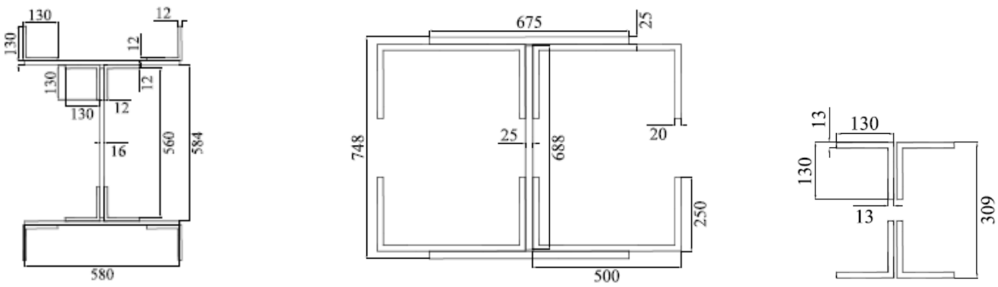
Fig.12 Double diagonal ten panel three span continuous truss with proposed third countermeasure suspension structure.

river bridge at which the ratio is 2.5. The suspension structure includes three different sections such as the main strings which are the curve members, the vertical tower posts which are above the bearing supports and the hanger posts which are the vertical posts except from the tower posts.

The cross sections of the suspension truss are estimated according to the visual observation of the Yalu river bridge in **Fig.13**. The main strings are supposed to be equal I section shape and the sections of the tower posts are proposed same as the vertical members above the supports and the other hanger posts are designed as the smaller size of I section than the vertical members of the truss. The cross sections of the suspension truss structure and the truss members of the Yalu river bridge are compared and the cross sections of the suspension truss structure are estimated. According to the Yalu river bridge, the cross section of the curve member main strings should be smaller than the top chord members and larger than the center bottom chord members in the middle span of the truss so that the large difference between the cross sections of the curve member main strings and the top chord members does not exist. The proposed cross sections of the suspension truss are shown in **Fig.14**.

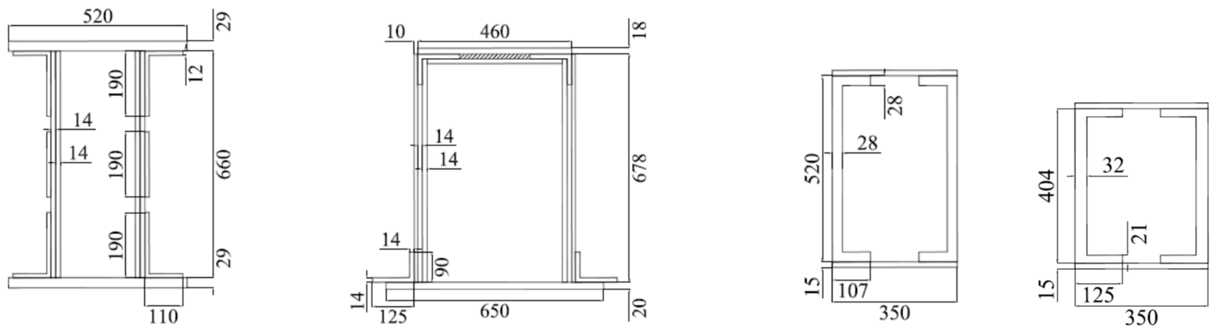
Fig.13 Bridge truss members and suspension structure of Yalu river bridge (Photo taken by Prof. Y. Takahashi)

Due to the lack of the details of the original structure, the cross sections of the members are estimated to support the full live load in addition to adding of third countermeasure suspension truss. The proposed estimated cross sections of the members to support full live load are shown in **Fig.15**. The improved structure including the suspension truss structure and proposed cross sections of members except from the existing members is shown in **Fig.16**.



(a) Main string (b) Tower post (c) Hanger post

Fig.14 Proposed estimated cross sections for suspension truss structure (Dimensions in mm).



O5 U11 D9 and D10 d11, D12 and d12

Fig.15 Estimated cross sections of three span truss with suspension truss structure to support full live load (Dimensions in mm).

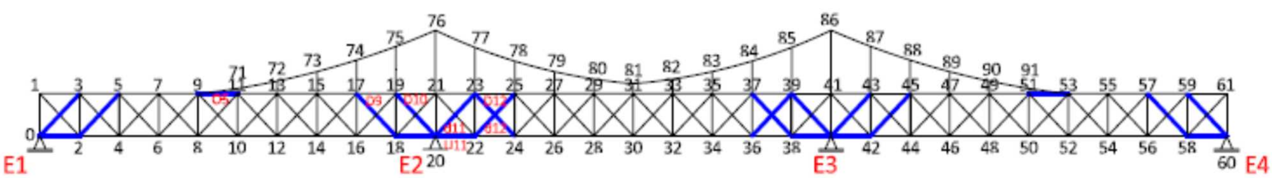


Fig.16 Ten panel three span continuous truss with suspension truss structure and estimated cross sections.

(3) Strength of suspension truss structure

It is important so that the strength and behavior of suspension truss steel members attached to the ten panel three span continuous truss bridge is enough to support the structure and applied load. Therefore, the strength of the curve member, the tower post and hanger post are checked for the intact structure from the numerical analysis of the ten panel three span continuous truss with the suspension structure. The curve member suspension truss is divided into segments at the connection of the curve member and vertical post for the numerical analysis and as same as the actual condition as shown in **Fig.17**.

The curve member strings and hanger posts are basically tension members and the tower posts are the compression members. The strength of the critical parts of the curve member strings, the tower posts and the hanger posts are checked and the stresses influence lines of the critical parts of the suspension truss structure are described in **Fig.18**.

The allowable compressive stresses are -108.46×10^6 N/m^2 for segment 7677, -108.17×10^6 N/m^2 for segment 2176 and -73.55×10^6 N/m^2 for segment 2377. The real acting stresses of the selected members of the suspension truss structure for the intact structure of the ten panel three span continuous truss are calculated and shown in **Table 3**. The strength of the critical parts of the suspension curve members, the vertical members and the tower posts are within allowable values for all loading cases and the proposed cross sections of the additional attached members are reasonable and acceptable to be used.

Table 3 Real acting stresses for the suspension truss components of the improved intact three span truss bridge with estimated cross sections (10^6 N/m^2).

Load / Member	D.L	L.L (+ve)	L.L (-ve)	L.L+ D.L	L.L- D.L
Segment 7677 (node 76)	9.51	66.39	-37.85	75.90	-28.3
Segment 2176 (node 21)	-1.96	31.97	-37.85	29.91	-39.8
Segment 2377 (node 23)	0.23	41.87	-41.19	42.17	-40.9

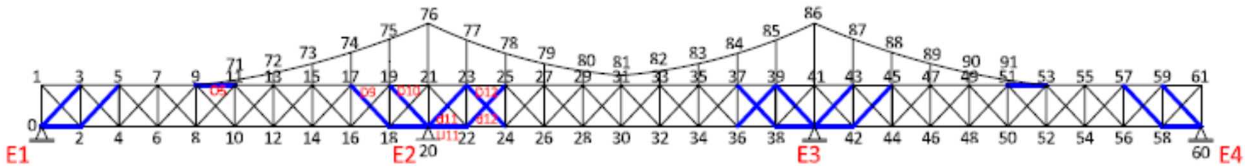
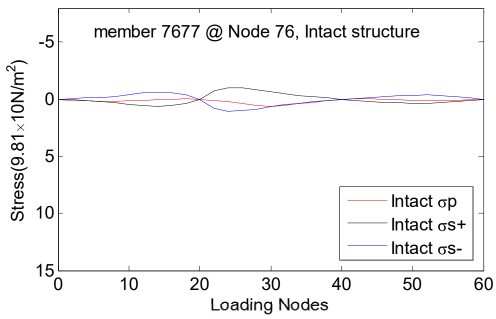
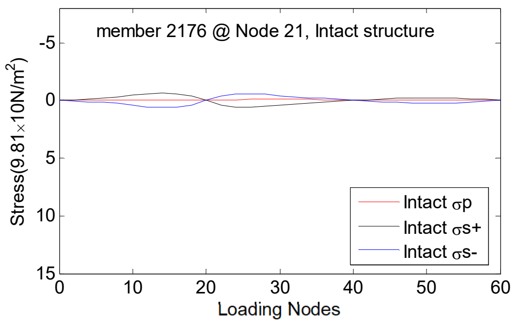


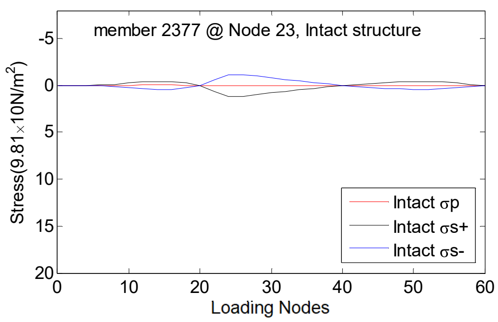
Fig.17 Ten panel three span continuous truss with suspension truss structure including segments and node numbers.



(a) Influence lines for curve member string



(b) Influence lines for tower post

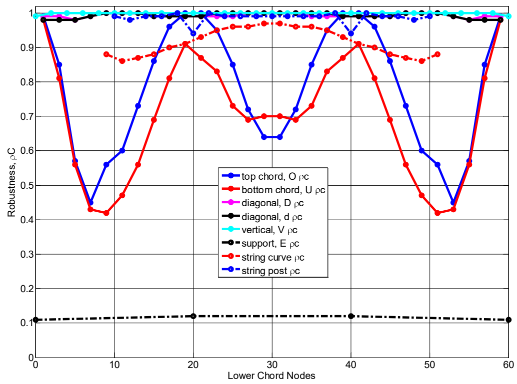


(c) Influence lines for hanger post

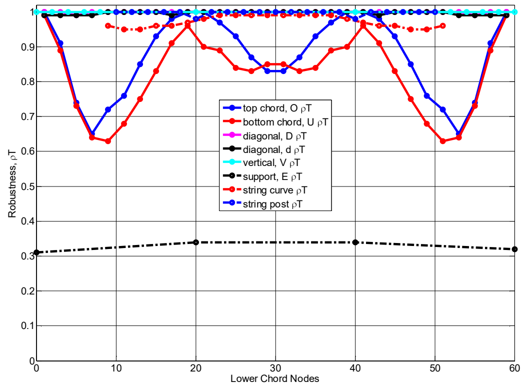
Fig.18 Influence lines of intact structure for the critical segments of the suspension truss structure.

9. ROBUSTNESS ASSESSMENT OF TEN PANEL THREE SPAN CONTINUOUS TRUSS WITH THIRD COUNTER-MEASURE

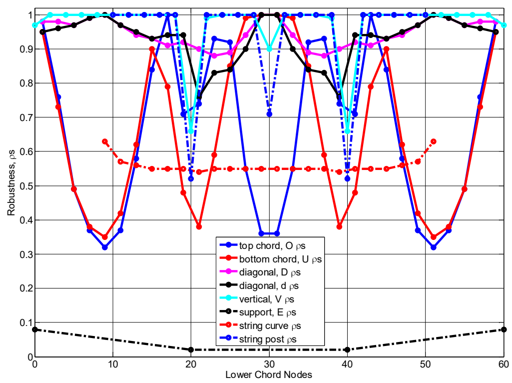
The robustness behavior of the double diagonal ten panel three span continuous truss bridge with the suspension truss structure and estimated cross sections is conducted by three different robustness indices illustrating with the influence lines and shown in **Fig.19**. After strengthening the double diagonal three span continuous truss with the suspension truss structure and estimated cross section of members to support full live load, the robustness of structure for one



(a) Robustness for conditioning of stiffness matrix



(b) Robustness for period



(c) Robustness for displacement

Fig.19 Robustness indices of ten panel three span continuous truss bridge with third countermeasure and estimated cross sections for damage of one member and external support.

damage member increase 1.34 times for the robustness index for the conditioning of stiffness matrix, 1.16 times for the robustness index for the period of structure and 1.89 times for the displacement robustness index in case of the damage of center bottom chord members in the middle span.

The increase in the robustness of structure is occurred for the damage of each member when the suspension structure are added to the upper part of the truss superstructure of ten panel three span continuous truss bridge. The effect of damage of the most severe exterior support E1 of ten panel three span continuous truss with the suspension truss structure is less influence than without the suspension truss structure and is almost the same with the effect of damage of the interior supports when including the suspension truss structure.

The robustness indices of the conditioning stiffness matrix and the period of structure of the curved strings and the hanger post are high level of robustness. The robustness index of the conditioning of stiffness matrix shows the curved hanger material steel members bring about 10% of the strength of the structure. However, the robustness index of the displacement of structure provides the intermediate level for the damage of the curved strings and the tower post. It indicates the hanger suspension truss are also important to the stability of the whole bridge in terms of the displacement index. It says that the addition of the suspension structure contributes the ordinary design purpose and the suspension structure are necessary for the safety of the structure.

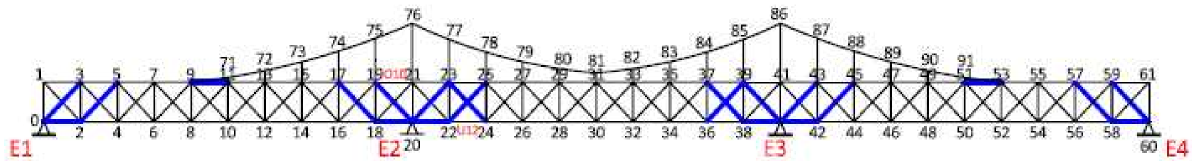
10. PERFORMANCE OF THREE SPAN CONTINUOUS TRUSS WITH THIRD COUNTERMEASURE SUSPENSION TRUSS AND ESTIMATED CROSS SECTIONS

(1) Influence lines of intact and damage structures

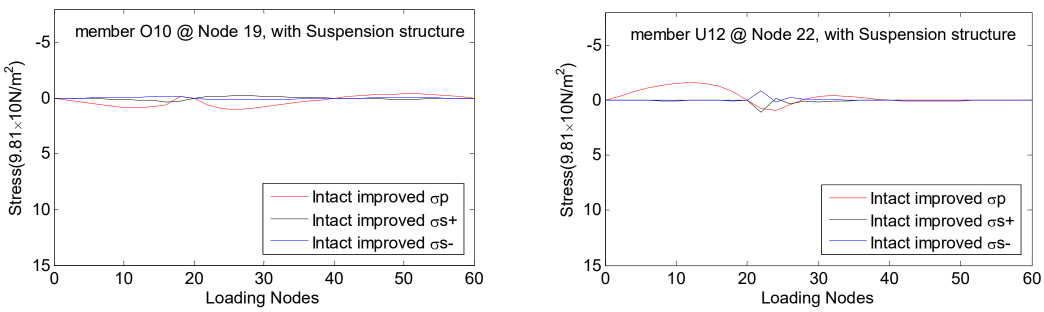
The behavior and strength of the double diagonal ten panel three span continuous truss including suspension truss structure and estimated cross sections is detected by the damage influence lines of the specific members for the intact and damage structure cases. The failure of the exterior support E1 is the worst case to be severe to the collapse of the continuous truss bridge. The performance of the strengthened structure is evaluated for the critical and most influential members. The stress influence lines of the critical members O10 and U12 are described for the intact structure with suspension structure and estimated cross sections in **Fig.20** and without suspension structure in **Fig.21**, for E1 damage and E2 damage structures with suspension truss in **Fig.22** and without suspension truss in **Figg.23**. In order to support the full live load, the development of structure includes not only attachment of the third countermeasure suspension truss structure but also estimation of cross section of members. As a result of addition of the suspension truss structure and estimation of cross section of members for the exiting ten panel three span continuous truss bridge, the primary stress of the most affected critical members reduce to 35% for the intact structure, 69% for the damage structure (E1 damage) and 13% for the damage structure (E2 damage). The primary stress of the chord members in the middle span of the intact structure reduces to 40% after adding the suspension truss structure and estimating cross sections of members. The addition of the suspension truss structure and estimation of cross sections for the double diagonal ten panel three span continuous truss bridge assist to promote the strength and to reduce the stresses of the members of the continuous truss bridge for the intact and damage structures. Besides, it also provides the aesthetics appearance of the entire bridge in addition to the provision of strength capability.

(2) Real acting stresses of intact and damage structures

The double diagonal ten panel three span continuous truss bridge is reinforced by estimating cross sections of members and adding third countermeasure suspension structure to the upper parts of the truss superstructure to support the full live load. In the previous section, the stress influence lines of the critical members for the intact and the damage structures (E1 damage case and E2 damage case) are expressed for the unit applied load along the span length of the bridge. In this section, the real acting stresses of the critical members for the intact and damage structures

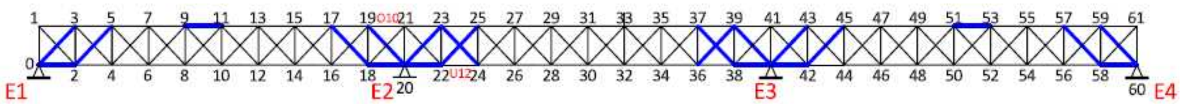


(a) Intact structure of ten panel three span continuous truss with third countermeasure and estimated cross sections

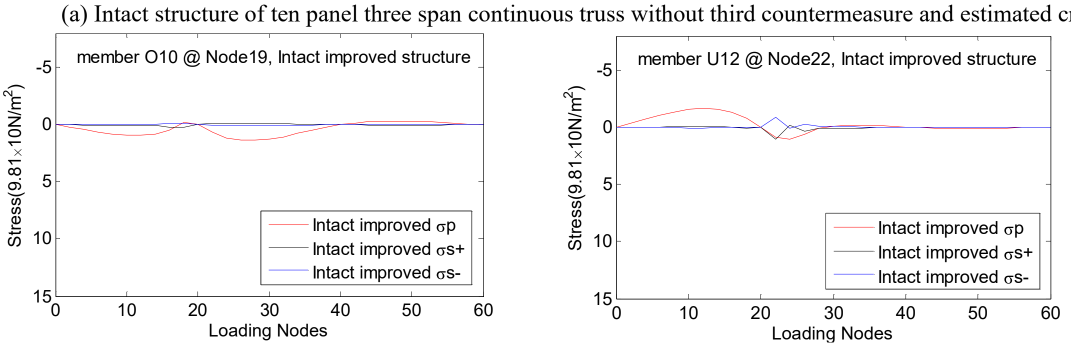


(b) Influence lines of intact structure for members O10 and U12

Fig.20 Influence lines of intact structure for members O10 and U12 in ten panel three span continuous truss bridge with third countermeasure and estimated cross sections.

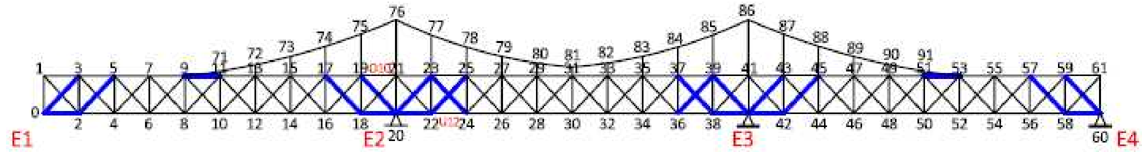


(a) Intact structure of ten panel three span continuous truss without third countermeasure and estimated cross sections

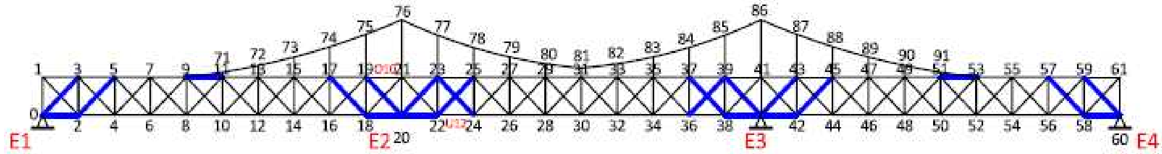


(b) Influence lines of members O10 and U12

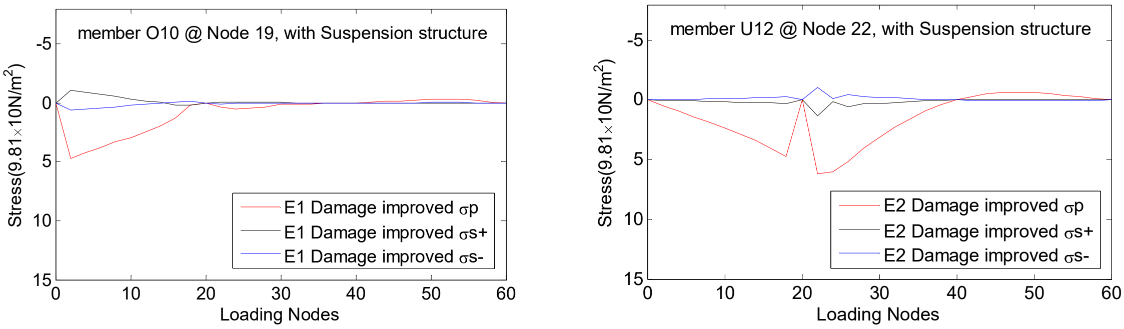
Fig.21 Influence lines of intact structure for members O10 and U12 in ten panel three span continuous truss bridge without third countermeasure and estimated cross sections.



(a) Damage structure (E1 damage) of ten panel three span continuous truss with third countermeasure and estimated cross sections

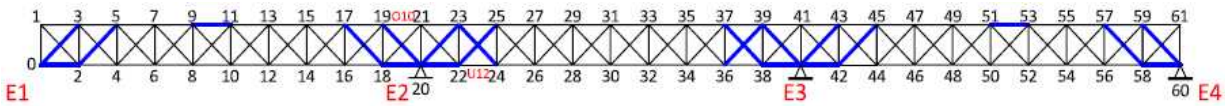


(b) Damage structure (E2 damage) of ten panel three span continuous truss with third countermeasure and estimated cross sections

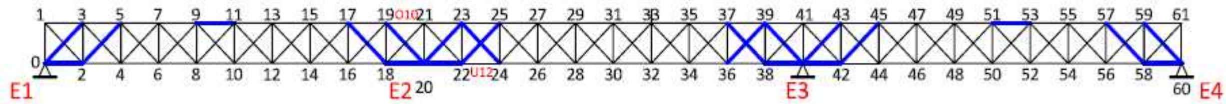


(c) Influence lines of members O10 and U12 for damage structure

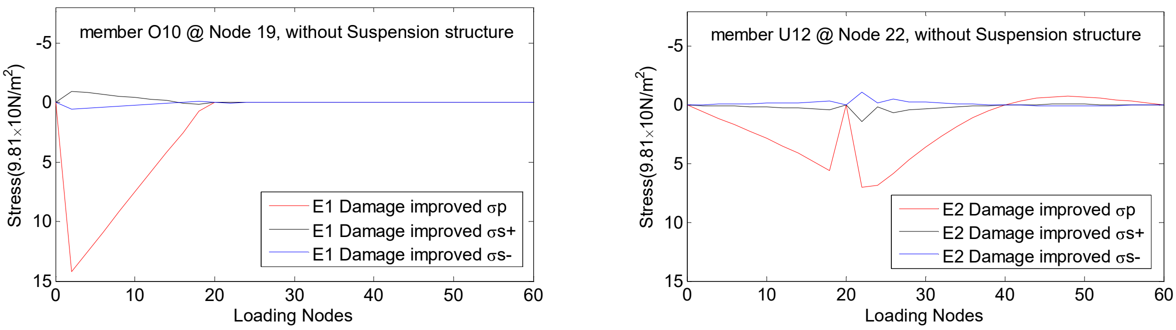
Fig.22 Influence lines of damage structure for members O10 (E1 damage) and U12 (E2 damage) in ten panel three span continuous truss bridge with third countermeasure and estimated cross sections.



(a) Damage structure (E1 damage) of ten panel three span continuous truss without third countermeasure and estimated cross sections



(b) Damage structure (E2 damage) of ten panel three span continuous truss without third countermeasure and estimated cross sections



(c) Influence lines of members O10 and U12 for damage structure

Fig.23 Influence lines of damage structures for members O10 (E1 damage) and U12 (E2 damage) in ten panel three span continuous truss bridge without third countermeasure and estimated cross sections.

are calculated for the real applied uniform dead load and live load. The uniform dead load is given as 2.45 $\times 10^6$ N/m^2 and the uniform live load is assumed as 7.36$\times 10^6$ N/m^2. In case of the dead load, the net area for the positive and negative stresses are considered as the dead load is fixed and uniform along the span length. In case of the live load, the area for the positive stresses and negative stresses are considered separately since the live load is moving along the span length. Then, the total stresses of the specific members are calculated for the dead load plus positive live load and for the dead load plus negative live load. The real acting stresses of members O10 and U12 for the improved intact structure without and with suspension truss structures and for the improved damage structures (E1 damage and E2 damage) without and with third countermeasure suspension truss structures are calculated to illustrate the effectiveness of suspension truss structure to the robustness of structure and to show that it is essential for the ordinary design purposes and shown in **Table 4** and **Table 5**.

As a result of improvement by adding the third countermeasure suspension truss structure and estimating the cross section of members, the intact structure with the suspension structure can support the full live load capacity despite the original intact structure and the intact structure without the suspension structure cannot support the full live load. This fact indicates that the suspension truss structure contributes the support for the ordinary design purpose and necessary for the safety of structure.

The damage structure in the estimated cross section of members (E1 damage or E2 damage) without the third countermeasure suspension truss structure cannot support the dead load while the damage structure in the estimated cross section of members with the suspension truss structure has the capability to support the dead load. This fact shows that the addition of suspension truss structure provides the development of the robust structure in case of loss of critical component. The structure is safe against the loss of the critical components.

The addition of the third countermeasure of suspension truss structure to the continuous truss bridge is the effective way to promote the robust structure for the purpose of bombing resistant structure and to sustain the safety of the bridge against the leakage of the critical or key component of the bridge structure. Besides, it also provides the support for the ordinary design purpose to assist the full live load carrying capacity for the intact structure case.

In order to develop the bombing resistant robust redundancy structure, the development includes the combination of the internal indeterminacy such as the double diagonal truss system, the external indeterminacy such as the continuous span truss and the addition of the third countermeasure of suspension truss structure and estimations of cross sections of members. The combination of the different countermeasures are proposed and recommended.

11. CONCLUSIONS

The linear gravity analysis of double diagonal ten panel three span continuous truss bridge is conducted using OpenSees software. The strategies of developing bombing resistant robust structures are suggested.

Table 4 Real acting stresses of intact structures of three span truss without and with third countermeasure and estimated cross sections (10^6 N/m^2).

Structure / Load Case	Intact (with suspension truss)	Intact (without suspension truss)
	Member O10 (node 19)	
D.L	19.70	27.24
L.L (+ve)	85.08	94.13
L.L (-ve)	-25.98	-12.41
DL + L.L	104.78	(96.96%L.L) 121.37
D.L – L.L	-6.28	14.83
	Member U12 (node 22)	
D.L	-20.72	-17.38
L.L (+ve)	29.19	33.64
L.L (-ve)	-91.36	-85.78
DL + L.L	8.47	16.26
D.L – L.L	-112.09	(99.91%L.L) -103.16

Table 5 Real acting stresses of E1 and E2 damage structures of three span truss without and with third countermeasure and estimated cross sections (10^6 N/m^2).

Structure / Load Case	Damage E1 (with suspension truss)	Damage E1 (without suspension truss)
	Member O10 (node 19)	
D.L	53.30	152.87
L.L (+ve)	201.29	485.48
L.L (-ve)	-41.39	-26.88
DL + L.L	254.59	638.34
D.L – L.L	11.91	125.99
	Damage E2 (with suspension truss	**Damage E2 (without suspension truss**
	Member U12 (node 22)	
D.L	111.88	131.13
L.L (+ve)	389.74	454.68
L.L (-ve)	-54.09	-61.27
DL + L.L	501.62	585.81
D.L – L.L	57.79	69.86

The influence lines are proposed for the robustness evaluation and development of robust structures. The most critical components whose damage severely destroy the structure are detected by the influence lines of robustness indices of structure. The damage of the internal indeterminacy and the damage of the external indeterminacy are considered. For the damage of internal indeterminacy, the most critical members are the center bottom chord members in all three spans as the cross sections of these members are the largest compared with the other bottom chord members. The failure of external indeterminacy is more severe than the failure of internal indeterminacy to destroy the structure. The damage of the exterior support is the most severe and most significant to cause the structure collapse for both the internal indeterminacy and external indeterminacy.

Then, the effect of loss of the critical component on the behavior of double diagonal ten panel three span continuous truss bridge are studied using the damage influence lines of stresses of the specific members for the intact and damage structures. The strategy of structural strengthening for the damage of most critical component (the damage of the external bearing) is proposed. Firstly, based on the damage of external bearing, the damage structure is strengthened by increasing the cross sections of the most severely affected members to sustain the dead weight of the damage structure. As a result of increasing the cross sections of the affected members, the most influential members due to the damage of the external support can sustain the dead weight of structure without collapse. The strengthening of structure by increasing the cross section of the affected members of the damage structure is the convenient way to improve the robust structure for the purpose of bombing resistant structures as they primarily proposed and to maintain the safety of structure when the structure is expected to experience the leakage of the critical components.

In order to support the full live load for the intact structure case and to develop into the bombing resistant robust structure in case of damage of critical components, the truss bridge is improved by adding third countermeasure suspension truss and estimating the cross section of members. The improved structure can support the full live load for the intact structure case. The strengthened three span continuous bridge with the suspension truss structure has the capability to resist the dead load when the most critical component of the exterior bearing support E1 or E2 is damaged while the improved structure without suspension truss structure cannot resist the dead load in case of damage of critical components. The addition of third countermeasure of suspension truss structure to the double diagonal ten panel three span continuous truss bridge is effective way to develop the robust structure for the purpose of the bombing resistant high redundant structure. The strengthening with the suspension truss structure to the continuous span truss bridge also provides the attractive and good aesthetics view in addition to the strength assistant purpose. Moreover, it also assists for the ordinary design purpose to support for passing the full percentage of live load for the intact structure case.

The robustness index of the displacement of structure in case of the damage of the suspension truss structure and the real acting stresses of the structural members without and with the suspension truss structure also show that the suspension truss structure is also necessary for the safety of the structure for the ordinary design purpose. To develop the bombing resistant robust redundant structure of truss bridge, the combination of the different countermeasures such as the internal indeterminacy (double diagonal system), the external indeterminacy (continuous span truss system), the suspension truss structure and the estimation of the cross section of members are proposed.

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