Robustness Evaluation of Double Diagonal Ten Panel Three Span Continuous Air-Raid Proof Bridge

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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 to use 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 conventional 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 hanger strings 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 and suspension hanger strings are recommended.

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

1. INTRODUCTION

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 are proposed as the design standard models for the purpose of locomotive trains at that time1). The bombing resistant double diagonal ten panel three span continuous truss bridge in which its behavior was conducted the linear gravity hand calculation method by the Japan researcher Dr. Oda (1941) 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 strings to the existing second countermeasure of double diagonal ten panel three span continuous truss bridge. 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 damage influence lines which are different from the conventional influence lines. The influence lines are primarily used to determine the critical position of the moving live load in the bridge design. 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 behavior of structure are detected using the conventional influence lines of stresses for the intact and damage structures. 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 computerized technology 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. Nonlinear is more accurate but computation takes longer time than the linear analysis. 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). The calculation includes not only the major primary stress but also the secondary stress due to bending and the rational design is performed. In addition, the design and construction of the Yalu River Bridge which is a friendship bridge between China and North Korea is described. The long span Yalu River Bridge was constructed by a series of the second type of bombing resistant double diagonal three span continuous truss and the third type bombing resistant structure which combined double diagonal three span continuous truss and suspension hanger strings. The advantages of addition of the suspension hanger strings to the continuous span truss bridge are presented. In relating with the structural resilience and structural strengthening of the damage structure, the traffic control technology from structural engineering point of view are presented. The structure is developed to improve the robustness of structure and to assist for carrying the full live load of locomotive train by adding the suspension hanger strings. The combination of different countermeasures are proposed for the development of robust structure.

2. HISTORY OF CONTINUOUS DOUBLE DIAGONAL 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 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. 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 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 damage influence lines. The structural strengthening and traffic control technology are presented. The suspension hanger strings are added to the existing continuous truss bridge to improve the robust structure and to avoid the failure when some components are lost and to assist for carrying the full live load for the intact structure case.

Fig.1 Present Imjin river bridge[1)

Fig.2 Present Yalu river bridge[1)

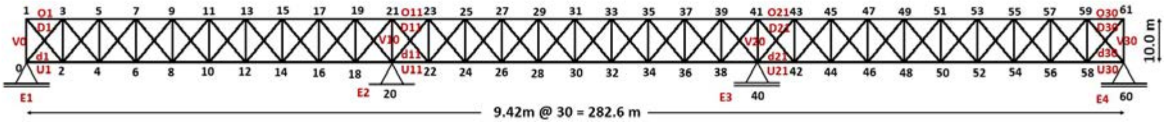
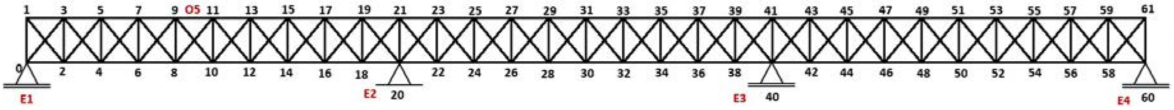
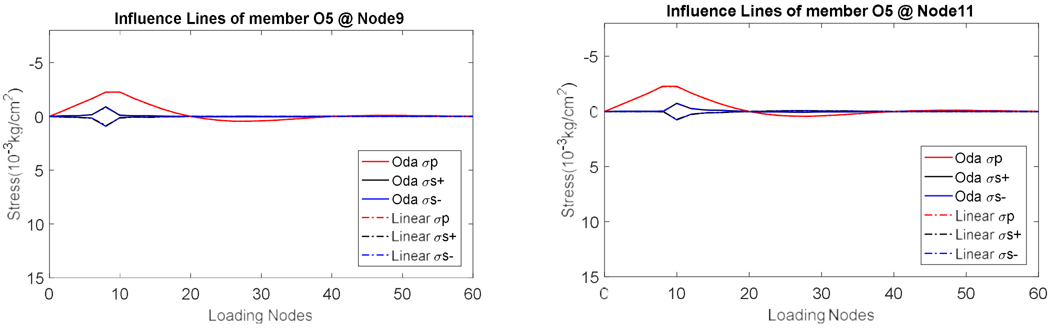


Fig.3 Double diagonal ten panel three span continuous truss bridge



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



(b) Influence lines of O5 at two nodes

Fig.4 Influence lines of member O5 in ten panel three span continuous truss bridge for two methods

(1) Verification of linear gravity analysis

The linear gravity analysis of ten panel three span continuous truss bridge is conducted by using OpenSees software. The weight of the steel truss members are applied at every nodes of the truss as the dead load. The bearing at the second support is fixed bearing and other three bearings are moveable bearings. The accuracy of linear gravity analysis is verified by comparing with the old hand calculation results conducted by the Japanese researcher Dr. Oda (1941). Two methods provide the same results and good accuracy is obtained. The stresses of the center top chord in the first span are calculated and shown in **Fig.4**.

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

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

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

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

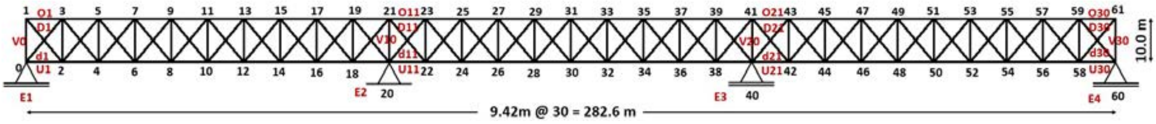
where the scripts ‘0’ refers to the original intact state and ‘1’ refers to the damage state of the system. ρ_c refers to the robustness index for the conditioning of the stiffness matrix of the structure, ρ_T refers to the index for the period of the structure and ρ_s refers to the index for the displacement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

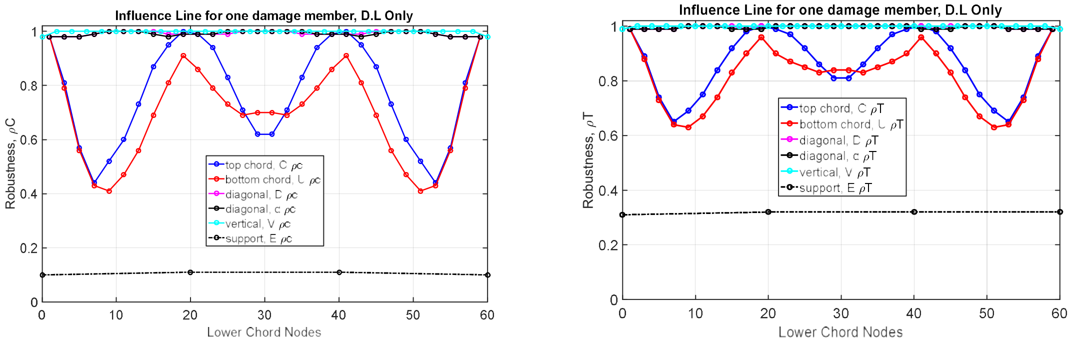
The three indices are adopted to predict the behavior of structure under the damage condition of internal indeterminacy and external indeterminacy. The most critical components of structure are identified.

4. DETECTION OF CRITICAL COMPONENT BY ROBUSTNESS INDICES

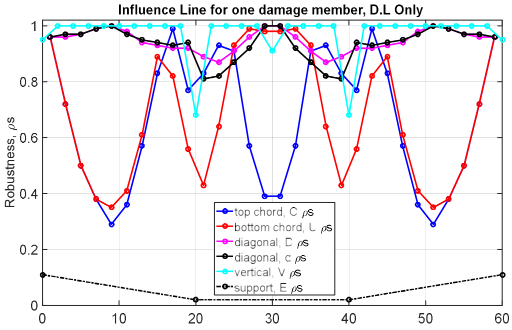
The damage influence lines are proposed for the robustness evaluation. The influence lines are primarily used to determine the critical positions for placing live loads in the bridge design. The influence lines are not related with the analysis of the earthquake bridge engineering[8]. However, in this study, the influence lines are used to inspect the behavior of structure for the robustness evaluation with the expression of robustness indices. The damage influence lines are attractive for the illustration of the damage member location and its influence on the structure performance.



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



(b) Robustness for conditioning of stiffness matrix (c) Robustness for period



(d) Robustness for displacement

Fig.5 Robustness indices of ten panel three span continuous truss bridge for damage of one member and external support

The damage of the components of the structure are considered as the internally indeterminacy and the externally indeterminacy of the structures as well. The totally damage of structural component is considered and the entire component is removed to identify the damage. 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 damage 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 damage influence lines of one damage member and external support for three robustness indices of ten panel three span continuous truss are shown in **Fig.5**.

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 is different in tendency with two indices. According to three robustness indices, the top chords and the bottom chords are the most effective members to cause the failure of the structure. When the damage of this 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 depended 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 carry 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 compare with the damage of one member in single span truss bridge, the effect of damage of one member in three span continuous truss bridge is smaller than the single span truss bridge due to the effect of the continuous system[8)]. In addition to the damage of the internal indeterminacy of the double diagonal three span continuous truss bridge, the damage of the external indeterminacy are also examined. 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 E1and 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.

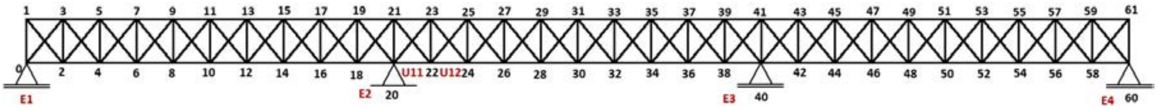
5. EFFECT OF DAMAGE OF CRITICAL COMPONENTS ON STRUCTURAL BEHAVIOR

(1) Influence lines of damage structure

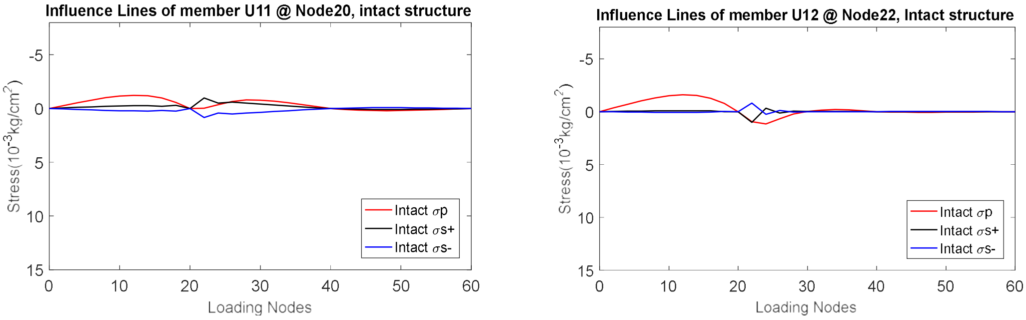
The effect of damage of critical component on the behavior of ten panel three span continuous truss bridge is inspected by using the conventional stress influence lines of the most affected members. In three span continuous type bridge, the damage of the external support is the largest influence to cause 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 influence lines of the members U11 and U12 for the intact structure are shown in **Fig.6** and for the damage structure are shown in **Fig.7**. 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 case.

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 influence lines of the members O9 and O10 for the intact structure are shown in **Fig.8** and for the damage structure are shown in **Fig.9**. 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 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.

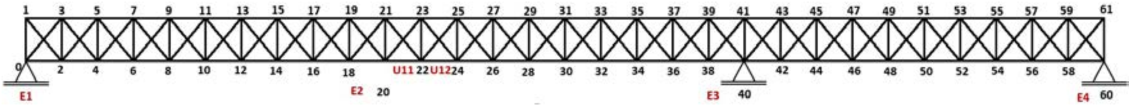


(a) Intact structure of double diagonal ten panel three span continuous truss bridge

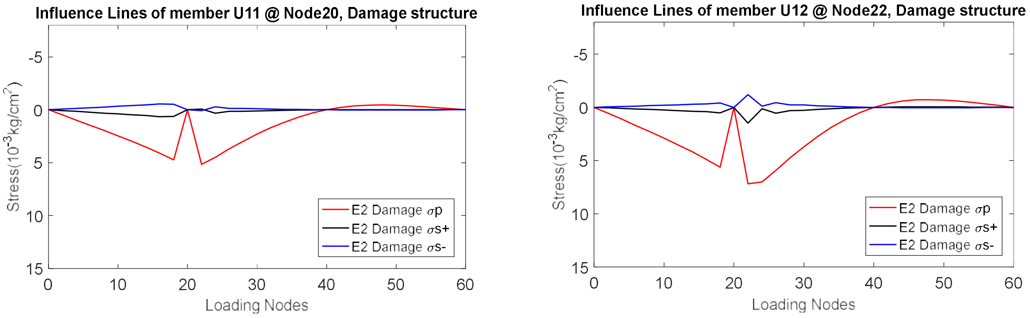


(b) Influence lines of intact structure for members U11 and U12

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

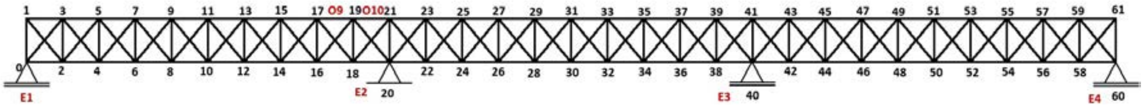


(a) Damage structure (E2 damage) of double diagonal ten panel three span continuous truss bridge

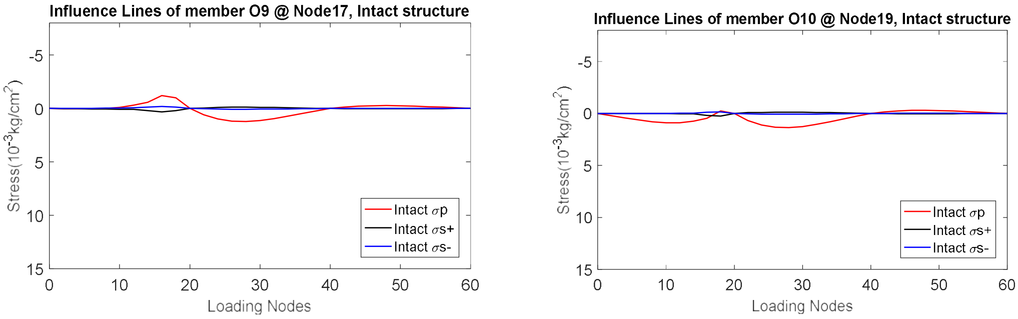


(b) Influence lines of damage structure for members U11 and U12

Fig.7 Influence lines of damage structure (E2 damage) for members U11 and U12 in ten panel three span continuous truss bridge

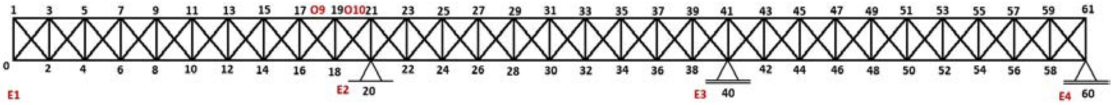


(a) Intact structure of double diagonal ten panel three span continuous truss bridge

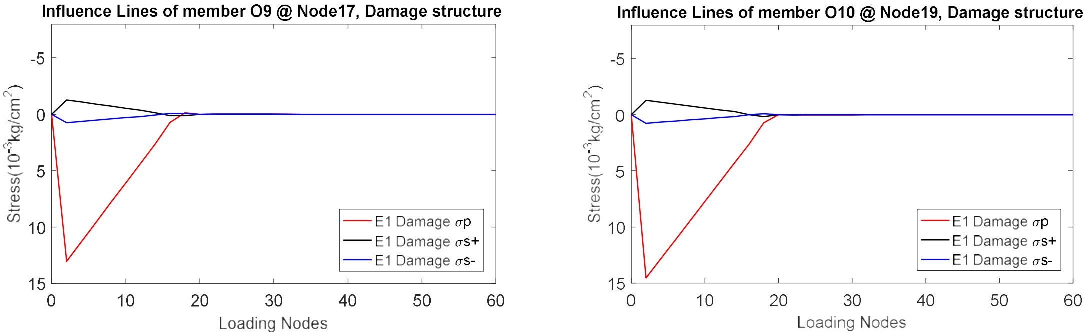


(b) Influence lines of intact structure for members O9 and O10

Fig.8 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.9 Influence lines of damage structure (E1 damage) for members O9 and O10 in ten panel three span continuous truss bridge

(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 positve 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 25kg/cm^2 and the live load is 75kg/cm^2. The allowable tensile strength of the steel is given as1200kg/cm^2. The allowable compressive stresses for U12, O9 and O10 is -1151kg/cm^2 and for U11 is -1149kg/cm^2.

The real acting stresses of members O9, O10, U11 and U12 for the 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 carry 68.40% according to the acting stresses of member U11 for the original intact structure case.

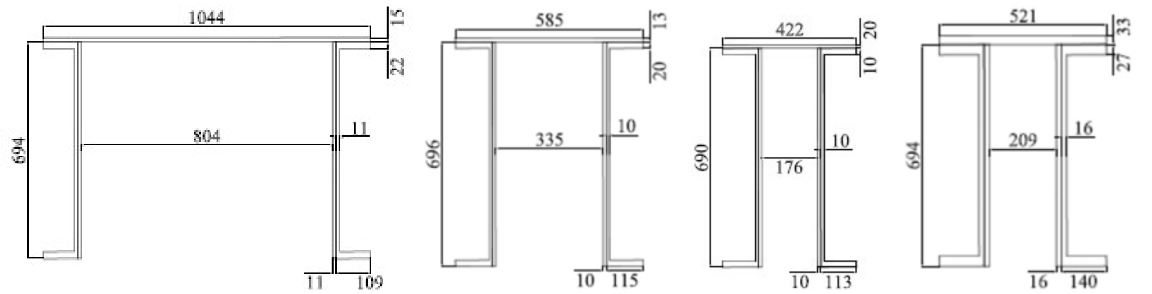
Table 1 Real acting stresses of the original intact and damage structures of original three span truss (kg/cm^2)

Structure Load Case	Intact (Origin)	Damage E2 (Origin)	Intact (Origin)	Damage E1 (Origin)
Member U11 (node 20)			**Member O9 (node 17)**	
D.L	-282.14	1011.94	73.25	1254.70
L.L (+ve)	419.72	3498.11	617.16	4121.92
L.L (-ve)	-1266.14 (68.40% L.L)	-462.29	-397.42	-357.82
DL + L.L	137.58	4510.05	690.41	5376.62
D.L – L.L	-1548.28	549.65	-324.18	896.89
Member U12 (node 22)			**Member O10 (node 19)**	
D.L	-165.49	1363.98	265.22	1581.91
L.L (+ve)	311.23	4728.97	996.08	5124.76
L.L (-ve)	-807.72	-637.02	-200.42	-379.02
DL + L.L	145.74	6092.95	1261.30 (95.16% L.L)	6706.67
D.L – L.L	-973.21	726.97	64.80	1202.89

6. IMPROVEMENT FOR ROBUST STRUCTURE

(1) Strengthening to resist dead load

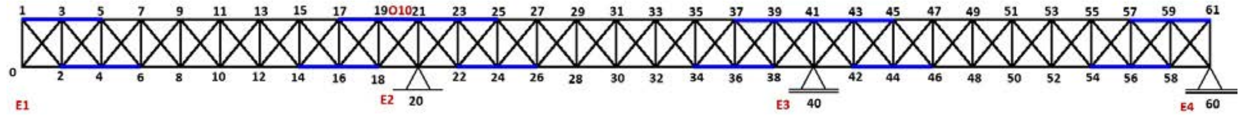
According to the robustness evaluation and the real acting stresses of the considered members, the damage of the external bearing is more severe than the damage of the single member to cause the collapse of structure. The failure of the external bearing E1 is the most influential and cause the failure 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 carry 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 in three spans are strengthened by increasing the cross sections of the severe affected 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 symmetrical and consistent of the structural system of the whole bridge, the corresponding symmetric members in the three



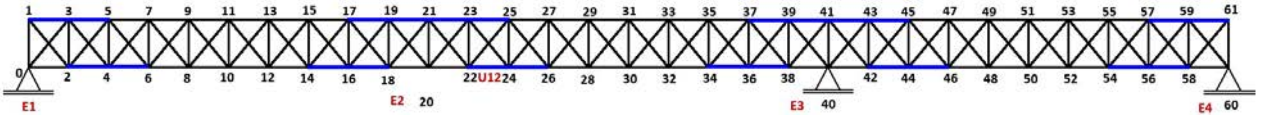
Original members O9, O10 Original member U8 Original member U9 Improved members U8, U9, O9 and O10

(Dimensions in mm)

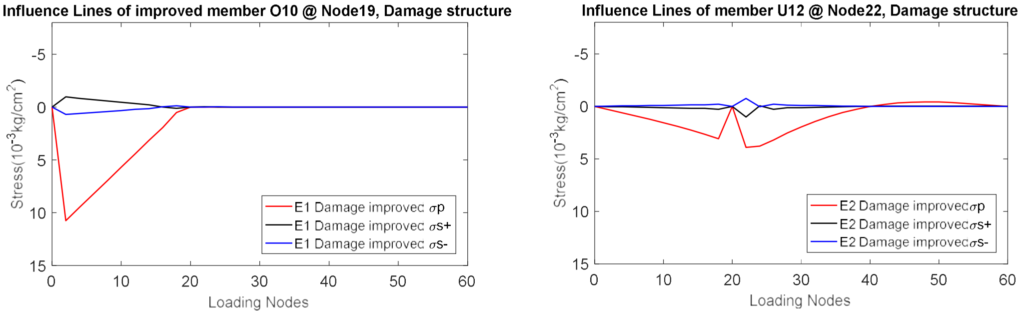
Fig.10 Estimated cross sections of original and improved members to resist dead load for damage structure (E1 damage)



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

spans are strengthened. The estimated cross sections of the original members and the improved members are shown in **Fig.10**.

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.11**. 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 of exterior bearing E1 also covers the damage of interior bearing E2 to support the dead load. The improvement is beneficial for the supporting of the damage structure and enhancement of the robust structure for the existing three span continuous truss bridge.

Table 2 Real acting stresses of the improved damage structure to resist dead load (kg/cm^2)

Structure / Load Case	Damage E1 (Improved)	Damage E2 (Improved)
	Member O10 (node 19)	Member U12 (node 22)
D.L	1184.08	740.95
L.L (+ve)	3836.21 (0.42% L.L)	2563.24 (17.91% L.L)
L.L (-ve)	-283.96	-340.40
DL + L.L	5020.30	3304.18
D.L – L.L	900.12	400.55

7. ADDING OF THIRD COUNTERMEASURE TO IMPROVE ROBUSTNESS

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 strings are added for the development of the bombing resistant robust structure to avoid the failure of structure when some structural components are lost1). 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 tie strings 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 strings 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 strings. The longitudinal profile is shown in **Fig.12**. 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 North Korea11).

(2) Proposed sections for suspension members

The proposed double diagonal ten panel three span continuous truss bridge with hanging suspension strings is shown in **Fig.13**. The height of the tower for the hanging strings is estimated based on the ratio of height of the tower post of the strings to the truss of the Yalu river bridge at which the ratio is 2.5. The hanging tie strings include 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 strings are estimated according to the visual observation of the Yalu river bridge in **Fig.14**. 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 hanger strings and the truss members of the Yalu river bridge are compared and the cross sections of the hanger suspension strings 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 are shown in **Fig.15**.

(3) Strength of suspension hanger strings

It is important so that the strength and behavior of suspension string steel members attached to the ten panel three span continuous truss is enough capacity

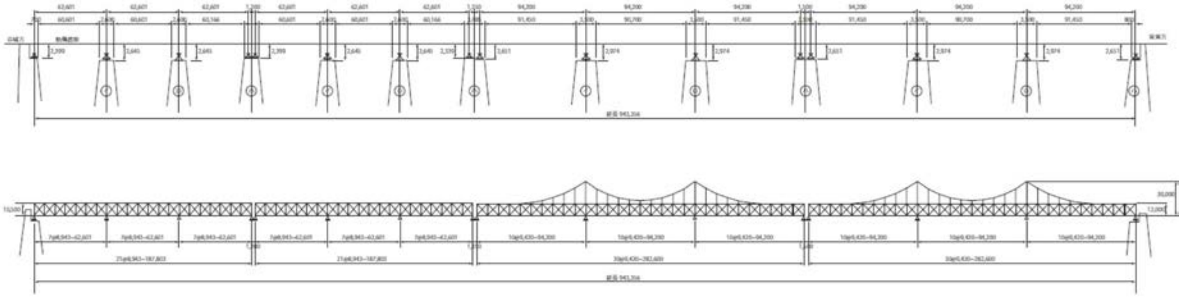
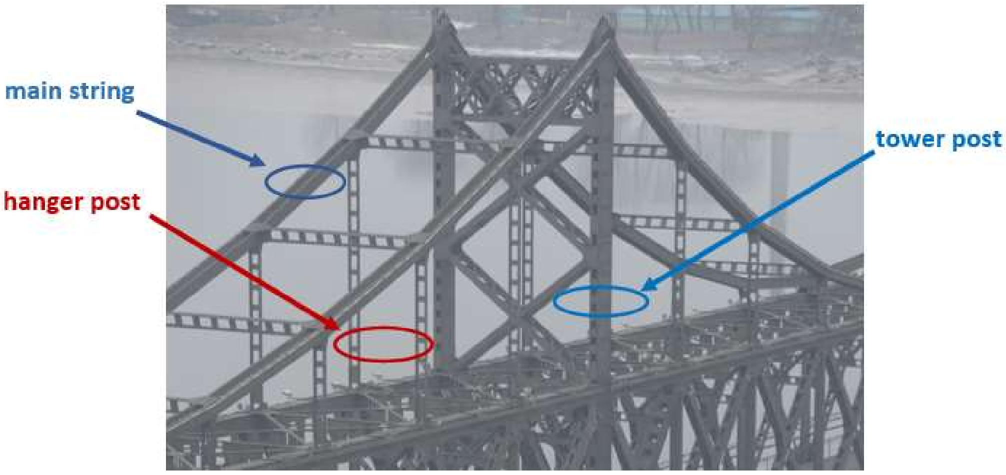
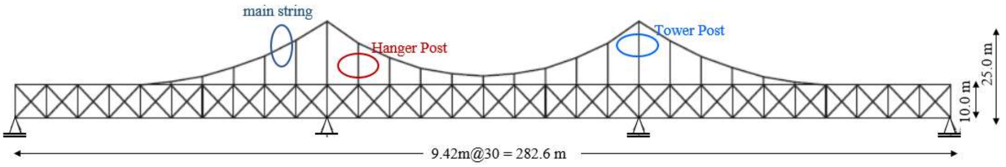


Fig.12 Longitudinal profile of Yalu river bridge$^{1)}$



(a) Suspension strings of Yalu river bridge (Photo taken by Prof. Y. TAKAHASHI)



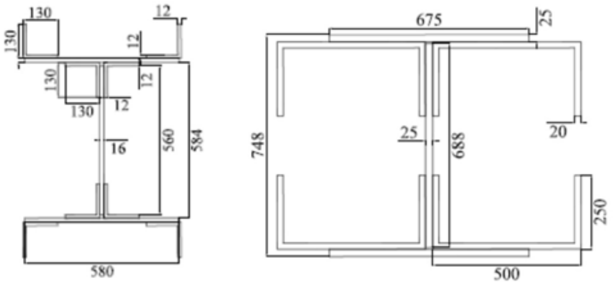
(b) Longitudinal profile for proposed bridge

Fig.13 Double diagonal ten panel three span continuous truss with proposed third countermeasure suspension strings

Fig.14 Truss members and suspension hanger strings of Yalu river bridge (Photo taken by Prof. Y. TAKAHASHI)

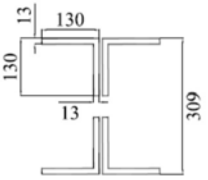
to support the structure and applied load.

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 strings. The curve member suspension string is divided into segments at the connection of the curve member and vertical post for the numerical analysis and same as the actual condition as shown in **Fig.16**. The curve member strings and hanger posts are basically tension members and the tower posts are the compression members.



(a) Main string

(b) Tower post



(c) Hanger post

Fig.15 Proposed estimated cross sections for suspension hanger strings (Dimensions in mm)

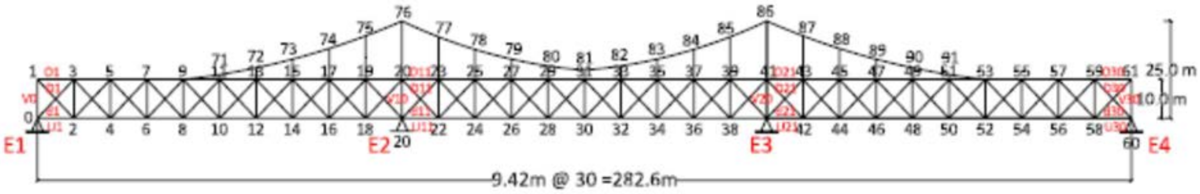
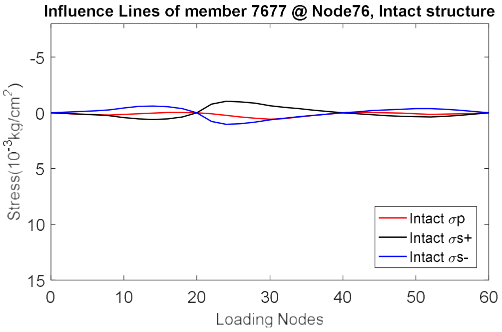
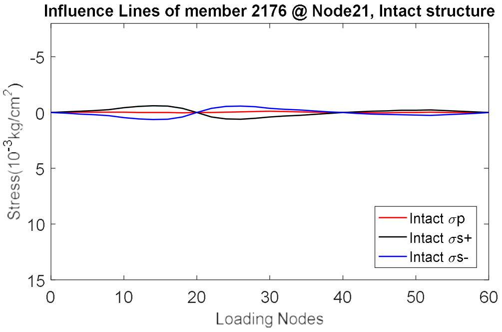


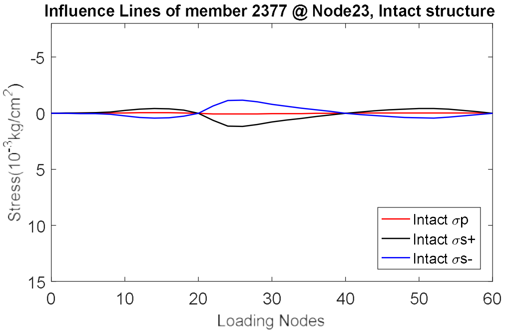
Fig.16 Ten panel three span continuous truss with suspension hanger strings including segments and node numbers



(a) Influence lines for curve member string



(b) Influence lines for tower post



(c) Influence lines for hanger post

Fig.17 Influence lines of the critical segments of the suspension strings of intact structre

Table 3 Real acting stresses of the suspension strings of the intact structure of three span truss bridge (kg/cm^2)

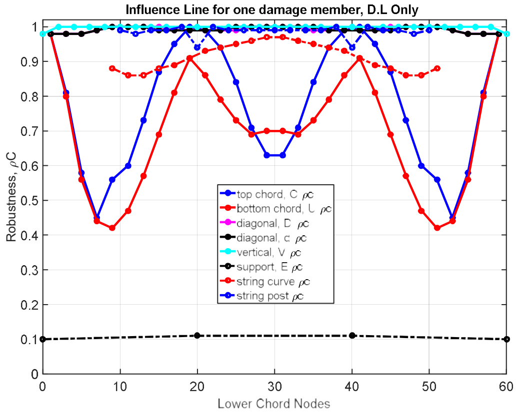
Load / Member	D.L	L.L (+ve)	L.L (-ve)	L.L + D.L	L.L-D.L
Segment 7677 (node 76)	101	699	-395	801	-293
Segment 2176 (node 21)	-21	331	-394	310	-415
Segment 2377 (node 23)	1.65	469	-464	471	-463

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 strings are described in **Fig.17**. The compressive stresses are -1106kg/cm^2 for segment 7677, -1103kg/cm^2 for segment 2176 and -750 kg/cm^2 for segment 2377. The real acting stresses of the selected members of the suspension strings 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 strings, 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 applied.

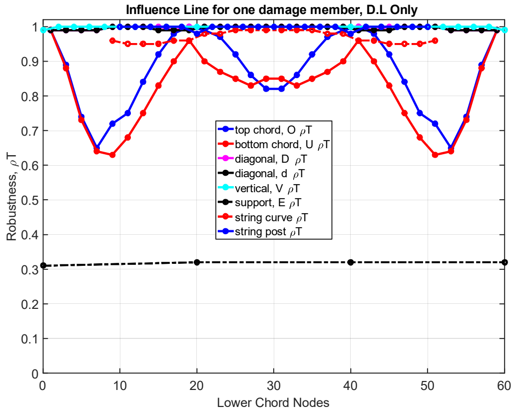
8. ROBUSTNESS ASSESSMENT OF TEN PANEL THREE SPAN CONTINUOUS TRUSS WITH THIRD COUNTERMEASURE

The robustness behavior of the double diagonal ten panel three span continuous truss bridge with the suspension hanger strings is conducted by the three different robustness indices expressing with the damage influence lines and shown in **Fig.18**. After strengthening the double diagonal three span continuous truss with the suspension tie strings, the robustness of structure for one damage member increase 1.39 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.

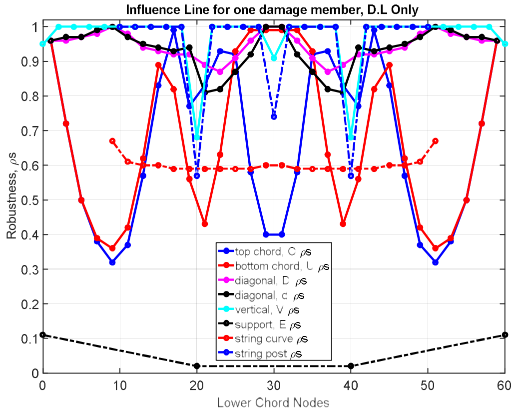
The increase in the robustness of structure is occurred for the damage of each member when the suspension hanger strings are added to the upper part of the truss superstructure of ten panel three span continuous truss bridge. The effect of damage of the most severe exterior support E1 of ten panel three span continuous truss with the suspension hanger strings is less influence than without the suspension hanger strings and is almost the same with the effect of damage of the interior supports when including the suspension hanger strings. The robustness indices of the conditioning stiffness matrix and the period of structure of the curved strings and the hanger post are high level. The robustness index of the conditioning of stiffness matrix shows the curved hanger material steel members carry 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 strings are also important to the stability of the whole bridge in terms of the displacement index. It says that the addition of the suspension strings contributes the ordinary design purpose and the suspension hanger strings are necessary for the safety of the structure.



(a) Robustness for conditioning of stiffness matrix



(a) Robustness for period



(a) Robustness for displacement

Fig.18 Robustness indices of ten panel three span continuous truss bridge with third countermeasure for one member damage and external support

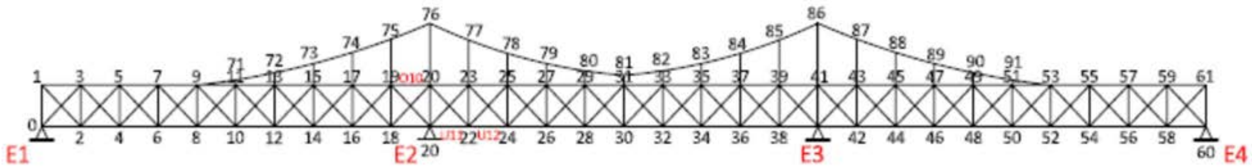
9. PERFORMANCE OF THREE SPAN CONTINUOUS TRUSS WITH THIRD COUNTERMEASURE SUSPENSION STRINGS

(1) Influence lines of intact and damage structures

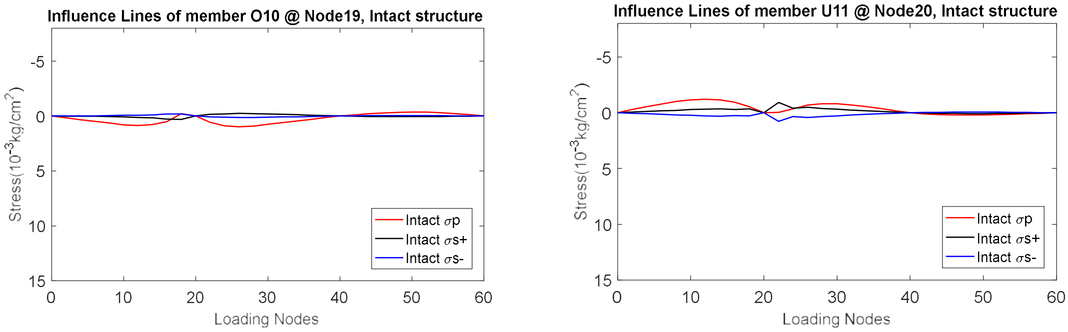
The behavior and strength of the double diagonal ten panel three span continuous truss with suspension strings is detected by the influence lines of the specific members. The failure of the exterior support E1 is the worst case to be severe to the collapse of the continuous truss bridge. The performance of the strengthened structure is evaluated for the critical and most influential members. The stress influence lines of the critical members O10, U11 and U12 are described for the intact structure in **Fig.19**, for the E1 damage structure in **Fig.20** and for the E2 damage structure in **Fig.21**. As a result of addition of the suspension strings by the proposed cross sections of structural steel members to the existing ten panel three span continuous truss bridge, the most affected primary stress of the critical members reduce to 34% for the intact structure, 67% for the damage structure (E1 damage) and 12% 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 strings. The addition of the suspension strings to the double diagonal ten panel three span continuous truss bridge assists 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

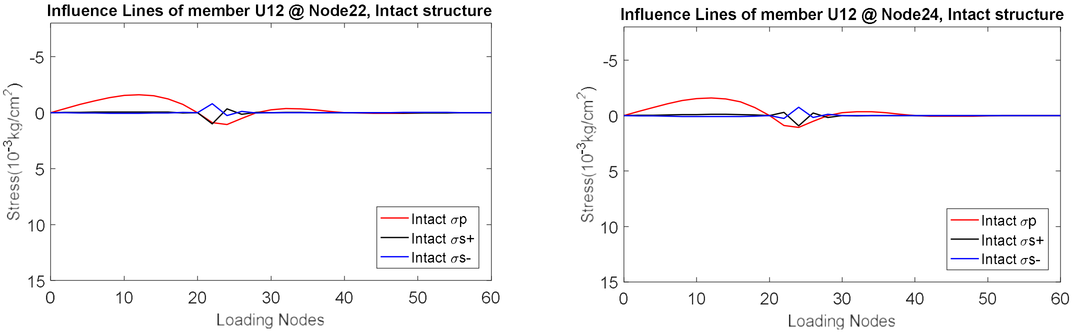
The double diagonal ten panel three span continuous truss bridge is reinforced by adding third countermeasure suspension strings to the upper parts of the truss super structure to develop the robustness and to avoid failure due to the damage of the structural components. In the previous section, the stress influence lines of the critical members for the intact structure and the damage structures (E1 damage case and E2 damage case) are expressed for the unit applied load along the span length of the three span continuous truss bridge. In this section, the real acting stresses of the critical members for the intact and damage structures are calculated for the real applied uniform dead load and live load. The uniform dead load is given as 25 kg/cm^2 and the uniform live load is assumed as 75 kg/cm^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 for members O10 and U11 are shown in **Table 4** and for member U12 in **Table 5**. As the advantage of addition of suspension strings to the three span continuous truss bridge, the real applied stress of the intact structure reduces to maximum of 49.10% according to the dead load plus live load combination case of the member O10. 33.01% of L.L can be allowed according to member O10 for the damage E1 case.



(a) Intact structure of ten panel three span continuous truss with third countermeasure

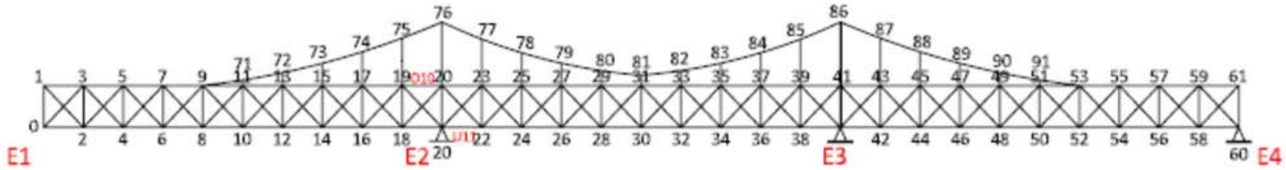


(b) Influence lines of intact structure for members O10 and U11

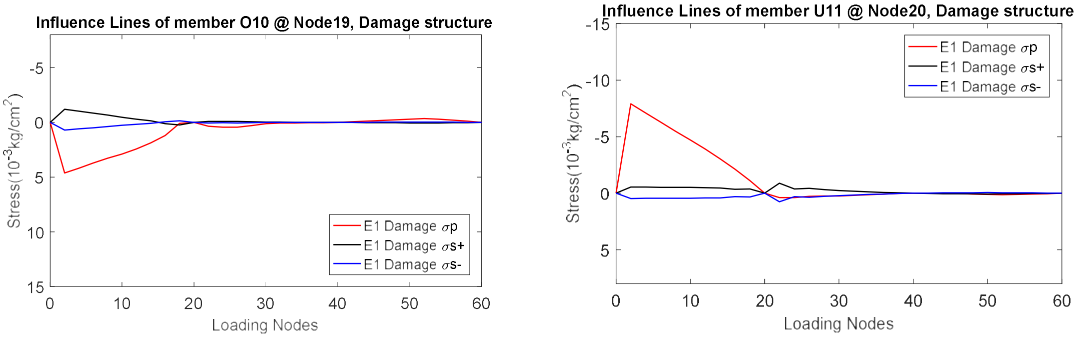


(c) Influence lines for intact structure for members U12

Fig.19 Influence lines of intact structure for members O10, U11 and U12 in ten panel three span continuous truss bridge with third countermeasure



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

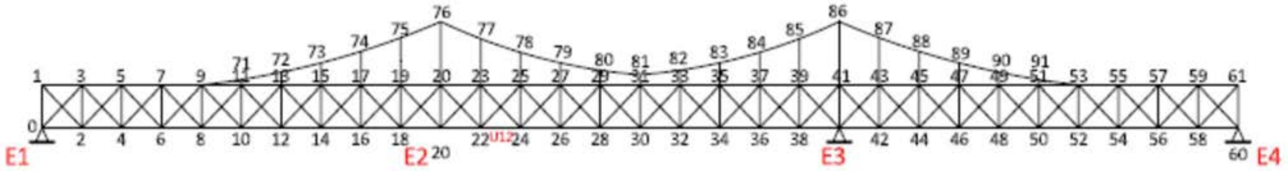


(b) Influence lines of members O10 and U11 for damage structure (E1 damage)

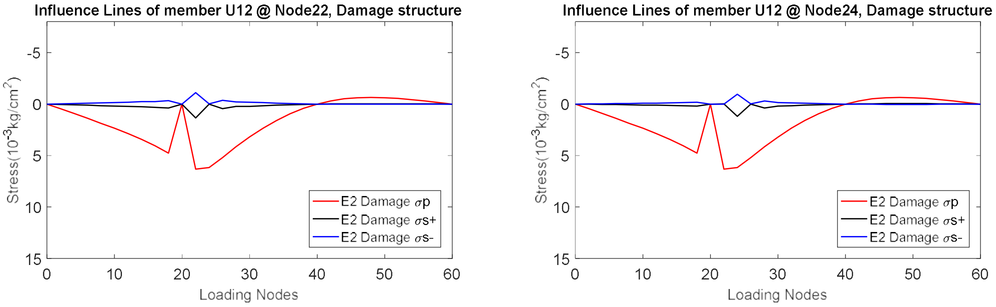
Fig.20 Influence lines of members O10 and U11 of damage structure of ten panel three span continuous truss bridge with third countermeasure (E1 damage)

For the damage structure (E1 damage) case, the applied stress of the damage structure reduces to 59.26% regarding with the dead load plus live load combination of the member O9. For the whole continuous truss bridge, the damage of the exterior bearing is the most severe case to cause the structural failure. After reinforcing the three span continuous truss bridge with the third suspension strings, the real acting stresses of the critical members are within the allowable limits for the dead load only case and the damage structure (E1 damage) can support the dead load without failure. However, the total live load cannot support for the damage of the external bearing E1 case and only 2.89% of live load can be allowed to pass the bridge according to the strength of the member U9 regarded with the negative live load case. As a result of addition of suspension hanger strings, the damage structure for E2 damage case also covers to resist the dead load and the live load can support only 1.20% according to the strength of U12.

The intact structure with suspension hanger strings cannot carry the full live loads and only 71.03% L.L can be allowed to pass the bridge according to the member U11 since the strength of original structure exceeds the allowable value. However, the damage structure can support the dead load according to the strength of critical members. The addition of the third countermeasure of tension hanger suspension strings 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 almost the full live loads passing for the intact structure case. In order to support the full live load capacity, the additional improvement is required.



(a) Damage structure of ten panel three span continuous truss with third countermeasure (E2 damage)



(b) Influence lines of damage structure (E2 damage) for member U12

Fig.21 Influence lines of damage structure for member U12 in ten panel three span continuous truss bridge with third countermeasure (E2 damage)

Table 4 Real acting stresses of intact and E1 damage structures of three span truss improved with third countermeasure (kg/cm^2)

Structure / Load Case	Intact	Damage E1	Intact	Damage E1
Member O10 (node 19)			**Member U11 (node 20)**	
D.L	187.03	524.13	-275.18	-946.50
L.L (+ve)	826.25	2047.31 (33.02% L.L)	403.91	598.23
L.L (-ve)	-265.17	-474.94	-1229.45 (71.03% L.L)	-3437.73 (5.88% L.L)
DL + L.L	1013.28	2571.44	128.73	-348.26
D.L – L.L	-78.14	49.19	-1504.63	-4384.22

Table 5 Real acting stresses of intact and E2 damage structures of three span truss improved with third countermeasure (kg/cm^2)

Structure / Load Case	Intact	Damage E2	Intact	Damage E2
Member U12 (node 22)			**Member U12 (node 24)**	
D.L	-202.15	1159.54	-203.11	1153.05
L.L (+ve)	268.10	4021.55 (1.01% L.L)	253.01	3919.53 (1.20% L.L)
L.L (-ve)	-874.54	-542.93	-862.33	-460.37
DL + L.L	65.95	5181.09	49.90	5072.59
D.L – L.L	-1076.6	616.61	-1065.44	692.69

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 hanger strings. The combination of the different countermeasures are proposed and recommended.

10. CONCLUSIONS

Double diagonal truss bridges were developed as the bombing resistant structures in the Korean Peninsula during the end of World War II by Railway Bureau of the Government-General of Chosen. The double diagonal single span truss bridges and double diagonal continuous span truss bridges were adopted as the design standard models as the high redundant bombing resistant structures at that time. The Japanese researcher Dr. Oda (1941) conducted the gravity linear analysis of the different types of truss by the displacement method in his doctoral dissertation. In this study, linear gravity analysis of double diagonal ten panel three span continuous truss bridge is conducted by OpenSees software. The weight of the structural members are applied at the respective nodes of the structural members. The effect of damage of structural components on the behavior of double diagonal ten panel three span continuous truss are evaluated by the damage influence lines of robustness indices of structure which indicate the location of damage member and its influence on the behavior of structure. The most critical components whose damage severely destroy the structure are detected. 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.

Moreover, 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 conventional influence lines 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 E1) is proposed. Firstly, based on the damage of external bearing E1, the damage structure is strengthened by increasing the cross sections of the most severely affected members to sustain the dead weight of the structure. The strength of the affected members are checked by comparing the real acting stresses of the original damage structure and improved damage structure with the respective allowable stresses of the specific members. After increasing the cross sections of the affected members, the most influential members due to the damage of the external support E1 can sustain the dead weight of structure without collapse. This improvement also covers to carry the dead load due to the damage of the interior support E2. 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.

Furthermore, the addition of the third countermeasure suspended strings to the double diagonal ten panel three span continuous truss bridge is proposed to improve the bombing resistant robust structure and to avoid the collapse of structure in case of damage of critical components of the bridge. The double diagonal ten panel three span continuous truss bridge is similar the Yalu river bridge which connects China and North Korea as a friendship bridge. It was a steel truss bridge 943.3 meters long, with 12 spans including four numbers of three continuous span truss. Two numbers of double diagonal three span continuous truss bridges are strengthened with the suspended strings at the upper part of the truss girder to improve robustness and to prevent the collapse when its components are leakage. In this study, the static linear gravity analysis of the double diagonal ten panel three span continuous bridge with the suspended hanger strings is conducted to observe the advantages of improvement by the suspension hanging materials. The strengthened three span continuous bridge with the suspended strings has the capability to resist the dead load when the most critical component of the exterior bearing support E1 or E2 is damaged. The addition of third countermeasure of suspended strings 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 hanger strings to the continuous span truss bridge also provides the attractive and good aesthetics outlook in addition to the strength assistant purpose. Moreover, it also assists for the ordinary design purpose to assist for passing almost the full percentage of live loads for the intact structure case. In order to support the full live load, the additional improvement is required. The robustness index of the displacement of structure in case of the damage of the suspension strings and the real acting stresses of the structural members without and with the suspension hanger strings show that the suspension hanger strings are also necessary for the safety of the structure for the ordinary design purpose. The addition of the suspension hanger strings to the three span truss bridge provides the strength to carry the dead load when the exterior or interior bearing support is lost and to increase the robustness and redundancy and to assist for passing almost the full live load capacity for the intact structure case. 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 hanger strings are proposed.

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