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Application of Influence Lines for Evaluation of Robustness of Blast Resistant Bridge Structure

MYA SAN WAI[1]・Kaito HANAFUSA[2]・Yoshikazu TAKAHASHI[3]

[1] Member of JSCE, Student, Dept. of Civil and Earth Resources Eng., Kyoto University（〒615-8540 Kyoto Daigaku Katsura, Nishikyo-ku, Kyoto, Japan）
[2] Chuo Fukken Consultants Co.,Ltd（〒533-0033 Higashi Nakajima, Higashi Yodogawa Ward, Osaka City）
[3] Member of JSCE, Professor, Dept. of Civil and Earth Resources Eng., Kyoto University（〒615-8540 Kyoto Daigaku Katsura, Nishikyo-ku, Kyoto, Japan）

1. INTRODUCTION

The double diagonal truss bridges were proposed by the Japanese researchers as the bombing resistant high redundant structure types during the end of the World War II for the railway bridge and transportation purpose. The Japanese researcher Oda (1941) conducted the linear gravity analysis of the double diagonal truss bridges in the research using the new calculation displacement method to check the behavior of the structure[1)]. Nowadays, it is possible to explore the linear and nonlinear analysis by using the computerized method to observe the behavior of the structure. The nonlinear redundancy analysis of the double diagonal single span truss bridge is carried out due to the dead weight of bridge to check the performance of the bridge under the damage of the structural members by using OpenSees software. The details cross sectional area of the members of the double diagonal truss bridges are designed following the existing cross sections of the truss members to conduct the nonlinear analysis. In the nonlinear redundancy and sensitivity analysis of the bombing resistant double diagonal single span truss bridge, the key elements are extracted. From the nonlinear analysis, the loss of the center top chord member or the loss of the center bottom chord member provides the high sensitivity that leads to the bridge collapse, but not expresses details in this study. It is found that the double diagonal single span truss bridge is not the highly redundant structure.

Furthermore, the effect of damage of structural components on the performance of the double diagonal single span truss bridge with regarded to the different robustness indices of structure are inspected by conducting the linear static analysis by using OpenSees software. The influence lines are primarily used to determine the critical positions for placing live loads in the bridge design to study the structural response under the moving load conditions. Ordinarily, the influence lines are not related with the analysis of the earthquake bridge engineering. In this study, the new ideas of influence lines are proposed to use in the evaluation of the robustness of the bridge structure due to the dead load. The most critical members are detected based on three robustness indices expressing with the influence lines. In the linear analysis of the evaluation of robustness of structure, the damage of the center bottom chord member or the damage of the center top chord member contributes low robustness values and it may cause the structure collapse. The damage structure due to loss of critical member is improved by increasing the cross sections of the directly affected members to reduce the drastically increase stresses and to promote to the high robust redundant structure by using the conventional influence lines of stresses. The strengthening of the structure is presented by using the influence lines of the robustness indices of structure and the conventional influence lines of the primary and secondary stresses of the directly affected members of the damage structure as the first proposal. In case of the damage of the critical member, the real acting stresses of structure are examined comparing with the allowable limits of structure and the bridge is retrofitting to recover the strength. At the same time, the train service is limited and the control of traffic loading is suggested for the improved damage structure as the second proposal.

2. SELECTION OF STRUCTURAL SYSTEM

During the end of the World War II, Japanese researchers proposed simple double diagonal single span truss bridges, which were high indeterminacy and redundancy structure, as the design standard models incorporating with the evaluation of the best design system starting from the single span truss bridges towards the more complicated continuous truss bridges for the good structural performance purpose. The double diagonal truss bridges were newly developed in the Korea Peninsula as the bombing resistant high indeterminacy structures at that time[1]. Adopting the simple double diagonal single span truss bridge, on the one hand, the effectiveness of the robustness indices on the system performance are evaluated regarding with the completely damage of the internally indeterminacy of the system (i.e., the damage of the structural members) and the critical members are observed. The proposal of structural strengthening is presented by increasing the cross sections of the directly affected members in case of the damage of the critical member to reduce the drastically increased stresses by illustrating with the influence lines. On the other hand, the proposal of the traffic control connected with the structural resilience strategy from the structural engineering points of view is presented based on the damage of the critical member considering the residual strength of the damage structure and damage improved structure for the different loading conditions.

3. REVIEW ON STRUCTURAL ROBUSTNESS

The failures caused by not only the exceptional loadings such as winds, earthquakes, impacts or explosions but also the gravity loadings may lead the progressive collapse that causes the disastrous impact to the safety of the structures. Adequately robust structures can decrease the impacts significantly. Robustness is defined as many definitions in the aspects of various researchers attitudes. 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[2]. Qualitative and quantitative approvals are provided for robust structure demands in Codes and publications. A quantitative measure would be beneficial to examine the robustness evaluation. Quantification of robustness can be categorized as risk-based measures, probabilistic measures and deterministic measures.

The deterministic measures of the structural robustness were developed by various researchers into the form of the properties of the structural system, both the system properties and the loading conditions, the structural strengths, the stored energy and the strain energy, the structural responses into the displacements, the base shear capacity and the damage based measures and so on.

S. Restelli, 2007 investigated several 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. 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 λi(K) denotes the ith 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 robustness indices related with the system properties and the loading condition 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 indices ρ_c and ρ_T are related to the properties of the structural system only and the index ρ_s is related to both the properties of the structural system and the loading condition[3)].

On the basis of knowledge reviewed from the literatures concerning with the quantification of the structural robustness, the robustness indices on the conditioning of the stiffness matrix and the period of structure and the displacement of structure are adopted to examine the performance of the structural system associated with the linear elastic behavior of the system. These 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.

4. EVALUATION OF ROBUSTNESS

To evaluate the performance of structure due to the damage of truss member, the linear gravity analysis is carried out using OpenSees software. The OpenSees analysis model of the double diagonal single span truss with the notation of node number and the identification of members is shown in **Fig.1**. The weight of the members are considered as dead load and applied at the connected nodes of the truss members. The damage is defined as one member in the truss structure. The damage of structural components is considered for internally indeterminacies for the robustness evaluation. The damage is stated by removing the entire member of the truss for the numerical simulation.

The robustness of double diagonal single span truss structure is presented using influence lines with regarded

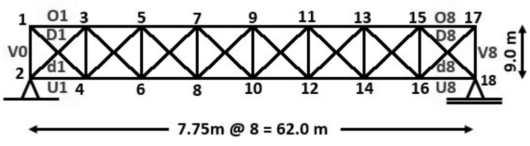


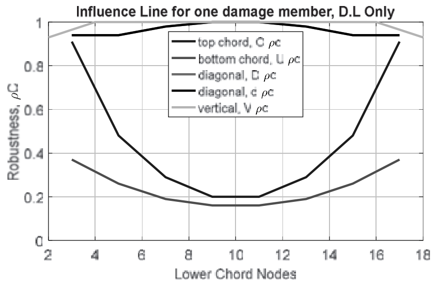
Fig.1 Double diagonal single span truss bridge

to the damage of structural members with the term "damage influence lines". The new idea is proposed to find out the location of the damage member and its minimum and maximum influence to the stability of structure reliably. It is attractive to demonstrate the damage location and its effectiveness to the structural performance. In the damage influence line diagram, the horizontal axis shows the node points at lower chord of the truss and the robustness values are assigned at the center of the panels where the members exist for the chord members and diagonal members, and at the node points for the vertical members along the truss and the vertical axis denotes the robustness values.

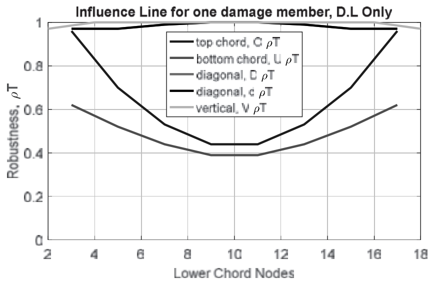
To represent the effect of damage member to the structural behavior using the influence lines diagrams, three robustness indices such as the robustness index of the conditioning of the stiffness matrix, the period and the displacement of structure whose characteristics have great influence on the performance of structures are considered. The robustness index ranges "0" for totally collapse of the structure to "1" for the full strength of the structure without collapse. According to the curvature of the influence line, the minimum value represents that the damage of member is the most influence to the collapse of structure and the peak value represents the least influence to the collapse of structure. From the influence line curvature, it can be seen efficiently the damage of which member is influence to what extend to the failure of the whole structure since the robustness indices show the representative of the behavior of the entire structure.

One damage member of the top chord member, the bottom chord member, the diagonal member and the vertical member are investigated and shown in **Fig.2**. For the top chord and the bottom chord members, the damage of center member is the most effective to cause the failure of structure. The optimum location is at the middle of the span. The influence line curvature is symmetric for all conditions as the configuration of the truss is symmetrical shape and the cross sections of the members as well. The robustness index of the period of structure represents higher robustness values than other two indices. The three robustness indices indicate that the tendency of influence of the damage of member decreases from the center towards the supports for the damage of chord members. This is due to the difference in the cross sectional sizes of the member, and the largest area occurs in the middle of the span for the chord members.

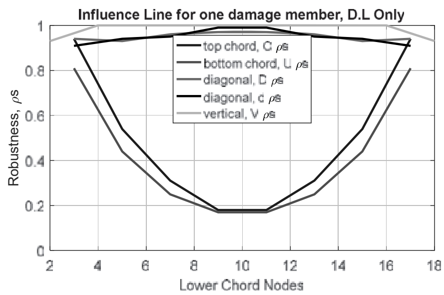
In contrary, for the diagonal members, the member



(a) Robustness for conditioning of stiffness matrix



(b) Robustness for period



(c) Robustness for displacement

Fig.2 Robustness indices for one damage member of original structure (D.L only)

near the support is the most influence to the structure collapse. The tendency of the effectiveness increases from the center towards the supports for the damage of diagonal members. For the vertical members, it indicates the damage of member at the support is the most influence and the inner vertical members provide full robustness values and have no influence to the structure collapse. Among them, the member O4 and U4 can be defined as the critical members since the damage of these members deliver the smallest robustness indices of 0.18 and 0.17 when the self-weight of the truss members are considered.

5. INFLUENCE LINES FOR DAMAGE STRUCTURE

In bridge engineering, the effect of moving live load is great influence on the bridge design in addition to its own weight of structure. Hence, the influence lines are popular to show the effect of moving load and its critical location in real bridge design. Based on the evaluation of the robustness of structure, the bottom chord member U4 is the most critical member whose capacity is great influence on the strength and hence, it is picked up to remove and the effect of the damage of the most critical member is observed using the conventional influence lines applying one unit load (1 kg) at every lower node of the truss and compared with that of the original intact structure. The damage structure removing the member U4 is shown in **Fig.3**. The influence lines of the primary and secondary stresses of the members in three panels at which the damage member is located and its adjacent two panels for the intact and damage structures are checked to identify the most influential members. According to the results, it is found that the differences in the stresses of the members in the same panel with the damage member are significantly large between the intact and damage structures and the stresses are increased drastically. The diagonal member D4 and the diagonal member d4 are directly affected and most influential when the member U4 becomes damaged. The member O4 is the second most critical member that effect on the strength of structure. The influence lines of the most critical member D4 and the second most critical member O4 for the intact and damage structures are shown in **Fig.4** and **Fig.5**.

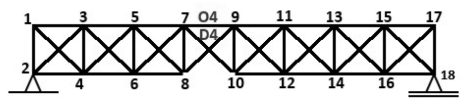


Fig.3 Damage structure due to loss of member U4

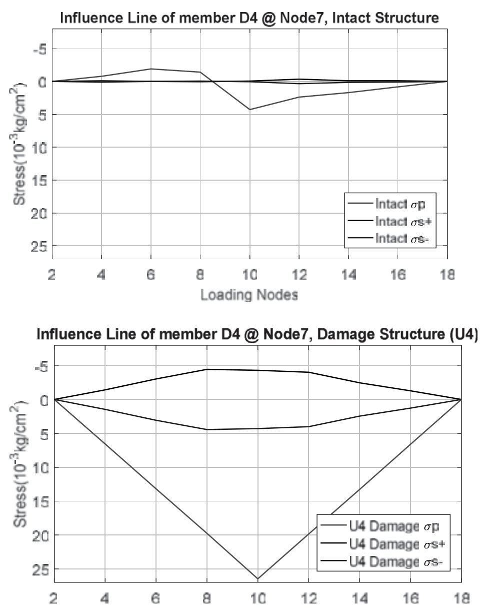


Fig.4. Influence lines of member D4 at node 7 for intact and damage structures (U4 damage)

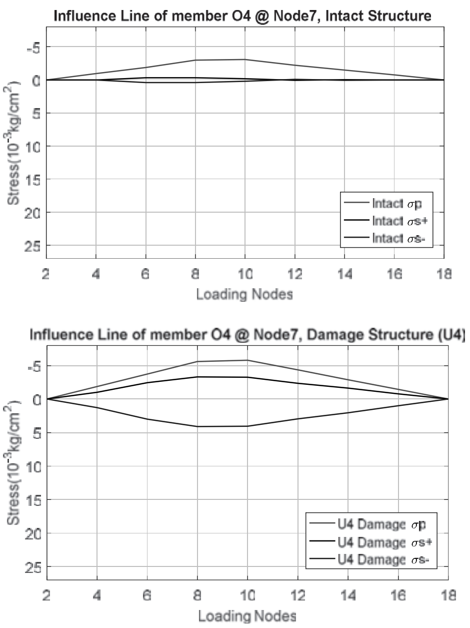
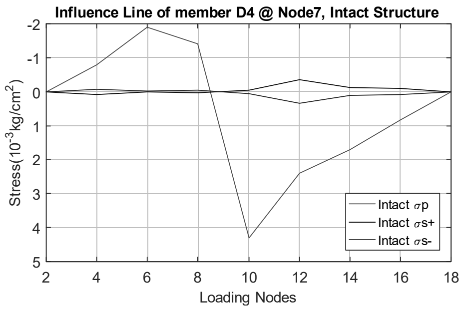


Fig.5. Influence lines of member O4 at node 7 for intact and damage structures (U4 damage)

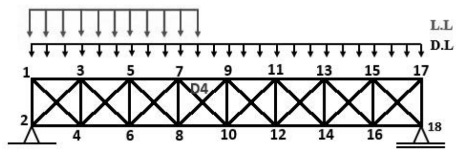
The primary stresses suffered at the center diagonal member D4 of the damage structure become 6 times larger compared with the original intact structure and the secondary stresses become larger 13 times at node 7 and 6 times at node 10 of member D4 respectively. In the top chord member O4, the primary stresses of the damage structure become larger 2 times, the secondary stresses occur larger 7 times at two nodes than the original intact structure.

(1) Real acting stresses of the original intact and damage structures

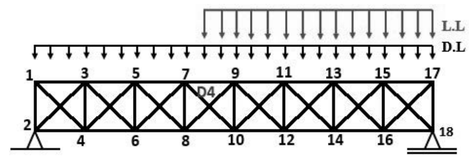
The primary and secondary stresses of the directly affected members for the intact and damage structures are observed using the stress influence lines. The stresses combination on the influence line diagrams are expressed based on the applied unit load at the specific locations along the truss bridge. In reality, the bridges are designed to support the responses of the maximum loads that they are subjected to. In this study, the own weight of structure and the locomotive train load are taken into accounted as the uniform distributed loads. For the realistically applied uniform dead load and live load, the product of the load intensity and the area under the influence lines gives the required responses. The uniform dead weight of structure is 25kg/cm and the uniform live load of the locomotive train including the impact load is 75kg/cm. In case of the dead load, it is considered the net area under the influence lines diagrams. The dead load is always fixed and acting on the whole structure. In case of the live load, the respective positive and negative area of the influence



(a) Influence lines of member D4 at node 7 for intact structure

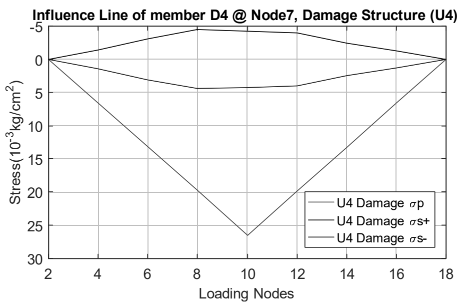


(b) Loads considered for maximum negative stresses

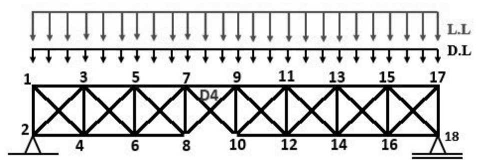


(c) Loads considered for maximum positive stresses

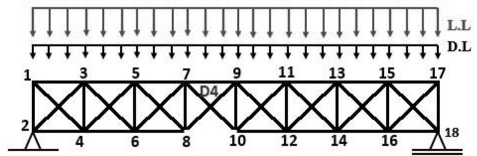
Fig.6. Loads considered for maximum stresses of member D4 at node 7 for intact structure



(a) Influence lines of member D4 at node 7 for damage structure



(b) Loads considered for maximum negative stresses



(c) Loads considered for maximum positive stresses

Fig.7. Loads considered for maximum stresses of member D4 at node 7 for damage structure

lines are considered. The maximum and minimum forces are obtained by combining the dead load plus the positive live load and the negative live load respectively. The consideration of the maximum positive stress and maximum negative stress for the member D4 at node 7 of the intact and damage structures are illustrated in **Fig.6** and **Fig.7.**

The primary and secondary stresses of the directly affected members for the actual loads are combined to check the safety of the structure. The allowable tensile strength of the steel is 1200 kg/cm^2. The allowable compressive strength are 1116 kg/cm^2 for the member O4, 713 kg/cm^2 for the original members D4 and d4 and 1123 kg/cm^2 for the member U4. The combined primary and secondary stresses of the directly affected members for the different loading cases for the different structure conditions are shown in **Table 1**. The five different loading cases are considered such as D.L only, L.L positive, L.L negative, D.L+L.L and D.L-LL. The total maximum and minimum stresses of the original members D4 and d4 of the intact structure for all loading cases are within the allowable tensile and compressive strength and the structure is safe satisfactorily and can sustain the total applied loads. The compression member O4 and tension member U4 were designed just close to the allowable values. It can said that the structure was well designed to resist the total dead load and live load safely. When the member U4 is damaged, the maximum stresses of the

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

Structure Load Case	**Intact (Origin)**	**Damage (Origin)**	**Intact (Origin)**	**Damage (Origin)**
Member O4 (node 7)			**Member O4 (node 9)**	
D.L	-255.06	-429.53	-252.19	-417.15
L.L (+ve)	66.57	1072.09	104.93	1264.82
L.L (-ve)	-831.77	-2360.6	-861.51	-2516.3
DL + L.L	-188.48	642.55	-147.25	847.66
D.L – L.L	-1086.8	-2790.2	-1113.71	-2933.46
Member D4 (node 7)			**Member D4 (node 10)**	
D.L	100	2047.94	100.00	2047.94
L.L (+ve)	549.7	7362.89	581.42	6626.71
L.L (-ve)	-249.69	-1219.0	-281.41	-482.86
DL + L.L	649.71	9410.84	681.43	8674.66
D.L – L.L	-149.69	828.89	-181.41	1565.08
Member U4 (node 8)			**Member U4 (node 10)**	
D.L	262.21		262.73	
L.L (+ve)	926.93		943.34	
L.L (-ve)	-140.3		-155.14	
DL + L.L	1189.15		1206.07	
D.L – L.L	121.9		107.59	

members D4 and d4 are tension and increase significantly and the stresses exceed the allowable limit even in the dead load only case and the structure cannot sustain the loads. In that case, the member O4 can support the dead load only case and cannot carry the live load.

6. STRATEGY TO IMPROVE ROBUSTNESS

(1) Avoid fall of structure without live load

The strength of the bombing resistant double diagonal single span truss bridge in case of the damage of the critical member is observed considering the actual loading cases that they are subjected to. In case of the damage of critical member U4, two diagonal members D4 and d4 recognize directly affected and the stresses increase drastically in the influence lines and the actual stresses exceed the respective allowable values. It is proposed to enlarge the cross section of the directly affected diagonal members to develop the robust structure. At least to avoid fall due to given dead load without live load, it is necessary to increase the cross sections of the directly affected members to D1 size that is larger 2 times in area and 3.79 times in moment of inertia of the original section. After increasing the cross sections of the directly affected diagonal members at the panel 4 and panel 5 into 2 times larger in area, the primary stresses of the affected members are dropped more than half. The maximum stress of the improved members for the damage structure for D.L only case is 962 kg/cm^2 and it is close to allowable value. The maximum stress for L.L positive is 3350kg/cm^2 and for L.L negative is -466 kg/cm^2 and only

(a) Original member (b) Improved member

Fig.8. Detailed cross sections of original and improved diagonal members for minimum (Dimensions in mm)

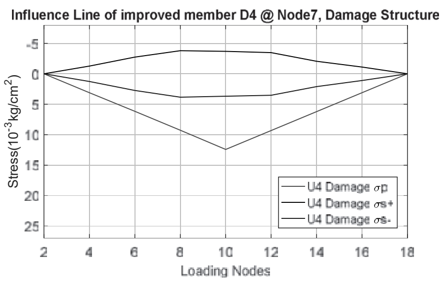


Fig.9. Influence lines of member D4 at node 7 for improved damage structure for minimum requirement

7% of live load is allowed. The detailed cross sections of original and damage structure is shown in **Fig.8** and the results of the improved member D4 are shown in **Fig.9**.

(2) Limited traffic capacity and structural resilience

To reduce the induced stresses to original state effectively and to increase the limited traffic capacity for passing, the affected diagonal members are increased to 5 times larger in cross sectional area and 19 times larger in moment of inertia of the original sizes as the increase in primary stress of damage structure is dominant and larger over 5 times than that of the intact structure and the area increase in 5 times is not larger than the smaller area of the chord members in that panel and also to reduce the effect of secondary stress. The stresses of the damage structure are compared with the stresses of the original state of the intact structure as the existing structure was well designed to resist the considered dead weight and live load of locomotive train passing. The detailed cross section of the improved member is shown in **Fig.10**. After strengthening the directly affected diagonal members, the stresses decrease drastically as shown in **Fig.11**. The development of the diagonal members is effective to reduce the drastically increased stresses of the affected two diagonal members of the damage structure and to improve the robust structure in case of the loss of the critical members.

The real acting stresses of the members O4 and D4 of the improved damage structure are calculated and shown in **Table 2**. The allowable compressive stress of the improved diagonal members develops to 987 kg/cm^2. The improved diagonal members of the damage structure are tension members and can sustain the strength for the dead load and cannot support the total live load. Therefore, it is proposed to control the train passing in that situation. The maximum 43% of the train loading is allowed to pass according to the strength of the improved diagonal member D4 in addition to the dead weight of structure. The structural resilience in case of the damage of the most critical members based on the realistically applied loads of the own weight of structure and the locomotive train loading and the traffic control strategy at this stage are proposed from the structural engineering points of view. This practice will be very helpful for the community to manage and control the railways and transportation services in case of the damage of the critical members of the truss bridge not only for the safety of structure but also for the human security aspect.

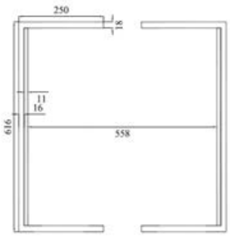


Fig.10. Detailed cross section of improved diagonal members to increase traffic capacity (Dimensions in mm)

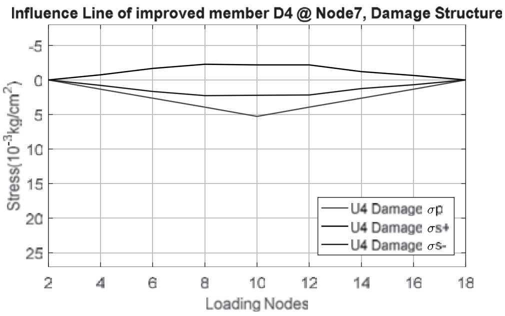


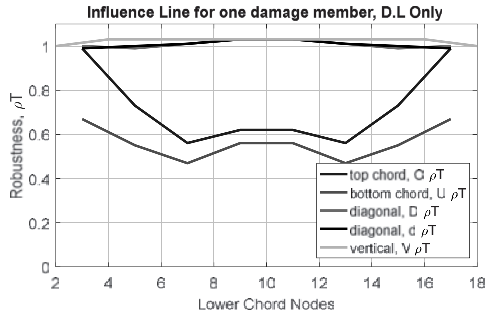
Fig.11. Influence lines of member D4 at node 7 for improved damage structure to increase traffic capacity

Table 2. Real acting stresses of the improved damage structure to increase traffic capacity (kg/cm^2)

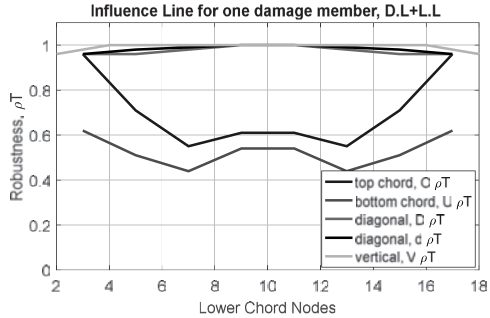
Member \ Load	D.L	L.L (+ve)	L.L (-ve)	L.L+ D.L	L.L- D.L
O4 (node 7)	-465	588	-1986	122	-2451
D4 (node 7)	406	1855	-635	2262	-228

(3) Robustness assessment of improved structure

After strengthening the directly affected center diagonal members of the single span truss bridge by increasing the cross sections into 5 times, the robustness of the improved structure is assessed with related to the dynamic characteristics robustness index of the period of structure for the D.L only case and D.L+L.L case since the effect of the live load is significant in the real bridge design and illustrated using the damage influence lines. The damage influence lines of the robustness index of the period of the enhanced structure for D.L only case and D.L+L.L case for one damage member are shown in **Fig.12**. As a result of improving the diagonal members in two center panels, the loss of the most critical members, the center bottom chord and top chord members cause the robustness of structure higher and those critical members become less influence to the capacity of the structure for D.L only case. In that case, the damage of U3 is more effective than the damage of U4. The efficiency of the member U4 and the member O3 are the same level to support the structure stability. The effect of live load is not significant on the robustness of structure as the robustness indices are the ratio of the values considered. The strengthening in four center diagonal members assists to be higher the robustness of structure in case of the damage of the most critical members, O4 and U4 and it also promotes these members less influence to the failure of structure.



(a) Robustness for period for D.L only case



(b) Robustness for period for D.L+L.L case

Fig.12. Robustness index of period of structure for one damage member of improved structure

7. CONCLUSIONS

The analysis of the bombing resistant double diagonal single span truss bridge is divided into two parts. In the first part, the proposal of the strengthening of structure is presented based on the damage of the critical member of the bridge by increasing the cross sections of the directly affected members to reduce the drastically increase stresses. The behavior of the intact and damage structures are expressed using the conventional influence lines of the stresses of the directly affected members. The critical members of the truss bridge are observed by evaluating the robustness of structure in three robustness indices and expressed their effectiveness using the damage influence lines. The strength of the damage structure are improved by comparing the strength of the original and damage structures using the conventional influence lines of stresses of the affected members and approved by the robustness indices of structure. It is efficient to increase the cross sections of the directly affected diagonal members to reduce the sudden increase of stresses without temporary supports and beneficial to develop the truss bridge into the high redundant and robust bombing resistant structure as they primarily proposed.

In the second part, the proposal of the traffic control in relation with the structural resilience strategy for the damage structure is presented. The strength of the double diagonal truss bridge in case of the damage of the critical member is predicted for the different loading cases from the influence lines. The stresses for the respective load cases are compared with the allowable stresses. In case of the damage of the critical member, the strength of affected members exceeds the allowable values and hence the structural strengthening is carried out to reduce the applied stresses for the damage condition. The damage structure is improved into two stages such as to sustain the dead load only and to carry the limited traffic capacity. The improved structure can sustain the dead load satisfactorily but it cannot support the total live load. In that situation, the train services are controlled and limited to allow passing for the improved damage condition of bridge. The traffic control methodology from the structural engineering points of view is essential in that situation and helpful to the community to maintain the safety of structure and the security of people as well. Moreover, it is helpful not to totally prohibit the use of the bridge even in the damage condition.

8. ACKNOWLEDGMENTS

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REFERENCES

1) Y. Takahashi, S. Kojima and M. S. Wai : Development and Construction of Double Diagonal Truss Bridges by Railway Bureau of Government of Korea (in Japanese), *Proc. of Historical Studies in Civil Engineering*, Vol.38, pp.261-270, 2018.
2) EN 1991-1-7, Eurocode 1: *Actions on Structures - Part 1-7: General actions - Accidental actions, CEN*, Brussels, 2006.
3) Biondini, F. and Restelli, S.: Damage Propagation and Structural Robustness, *Life-Cycle Civil Engineering,* Taylor & Francis Group, London, 2008.