Redundancy analysis of an old steel railway bridge: A case study of Hardinge bridge

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ABSTRACT: Hardinge Bridge is the first railway bridge in Bangladesh which is made up of prefabricated trusses and most notable thing is that this steel truss bridge is almost 100 years old. As an old steel bridge, fatigue crack and rust can affect steadily on truss members. Steel truss bridges which have not any redundancy can progressively collapse over the entire span if a single primary member or gusset plate connection of the main trusses is damaged. This paper describes the redundancy analysis of Hardinge bridge after fracture of its different primary members. The analysis is conducted through commercially available STAAD.pro software considering dead load and moving train load conditions. Truss bridge is modeled to consider Bangladesh Railway supplied data where WDM2 Co-Co type for locomotive and Bo-Bo type for bogies are considered as a train load. At first, axial stresses in different members of the bridge are calculated, then different members are removed considering those damaged due to fatigue or rust effect and subsequently the axial stresses of adjacent members are calculated. Finally, redundancy of the bridge is described with respect to the percentage of change in axial stress before and after fracture. From this analysis it is observed that increase of axial stress of the adjacent member varies with different damage scenario. Therefore, regular supervision and proper maintenance are necessary for the members which highly affect the stress behavior of adjacent members.

1 INTRODUCTION

Hardinge Bridge is a steel railway bridge over the Padma River located at Paksey in western Bangladesh. It is the first railway bridge in Bangladesh and its service life is almost 100 years. As an old steel truss bridge, fatigue crack and rust can affect steadily on its truss members. Fatigue occurs when a material is subjected to repeated loading and unloading. It is one of the major causes of truss member failure. This problem generally act when the bridges reaches 35 to 50 years of its service life (URS corporation, 2006). Rust effect is another major problem for steel structures. Steel structure reacts with oxygen in presence of air moisture or water and formed rust. Continuous rusting effect corrodes the members of bridge. But the most mentionable thing is that steel truss bridges can progressively collapse over the entire span for the failure of a single primary member or gusset plate connection, if the bridge is not redundant. One of the recent tragic examples of such progressive collapse of the entire bridge due to the loss of a single gusset plate is the case of I-35W steel deck truss bridge located in the city of Minneapolis in United States. On August 1, 2007, it suddenly collapsed killing 13 peoples and injuring 145 peoples (Astaneh-Asl, 2008). In Japan another steel truss bridge over the border between Tokushima and Kagawa region collapsed in Nov. 2007. Fortunately nobody was injured by this collapse (Okui et al. 2010). I-5 Skagit River Bridge, Mount Vernon, Washington also collapsed in May 23, 2013, injuring 3 peoples due to fracture of a single member (komo, 2013).

These experiences imply the necessity of the investigation into the structural behavior when a single primary member of truss fails. Especially it is important to identify the fracture critical member, the failure of which would lead the progressive failure of the bridge span (Yamaguchi *et al*. 2011). Throughout the years, researchers have developed many methodologies to truly analyze the behavior of truss bridges and depict their true redundancy in the case of collapse, based on deterministic and probabilistic techniques. The latest NCHRP study dealing with the issue of redundancy was in report number 406 (Ghosn & Moses, 1998), where redundancy is defined as the capability of the bridge to continue to carry loads after the failure of one or more of its member. Okui *et al.* (2010) also conducted a finite element analysis for a 3 span continuous bridge to evaluate the load carrying capacity after a failure of a member.

There are many methodologies for describing redundancy. In this study the redundancy of Hardinge Bridge is described with respect to the percentage of change in axial stress before and after fracture of a single member.

2 REDUNDANCY ANALYSIS OF HARDINGE BRIDGE

As truss members carry only axial force, redundancy can be described with respect to the percentage of change in axial stress before and after fracture. It is known that truss is a structure of connected elements forming one or more triangular units (Shedd & Vawter, 1990) and this triangular unit distributes the load of the bridge to the connected members and maintains a balanced condition. If one member of this triangular unit is damaged then the unit becomes unbalanced and for this reason whole truss could be progressively collapsed. So, it is very essential for the truss bridge to check the load carrying capability after fracture of a single primary member and identify the fracture critical member.

The analysis is conducted through commercially available STAAD PRO software. At first axial stresses of different members of this bridge are calculated, then different members are removed, considering those are damaged due to fatigue or rust effect; thus, axial stresses of adjacent members are calculated. Finally, redundancy of the bridge is described with respect to the percentage of change in axial stress before and after fracture.

2.1 *Description of Bridge Geometry*

As Hardinge Bridge is a 100 years old bridge, it is very difficult to collect all appropriate design data. Many data are ruined due to proper maintenance. Office of the Bridge Engineer (West), Bangladesh Railway, Paksey compiled some of the data together and most of the data used in this paper are taken from those data.

The total length of Hardinge Bridge is 5940 ft. There are 16 piers and 15 spans each of 345 ft long. The width and height of the bridge is 32 ft and 49 ft respectively. There are two boxed shape top chord and bottom chord in a span. Vertical members are spaced at 15.7 ft and the longitudinal 4 stringers are spaced at 6 ft center to center. There are 23 cross beam in a span spaced 15.7 ft center to center. The geometric dimensions of Hardinge Bridge are shown in Figure 1.

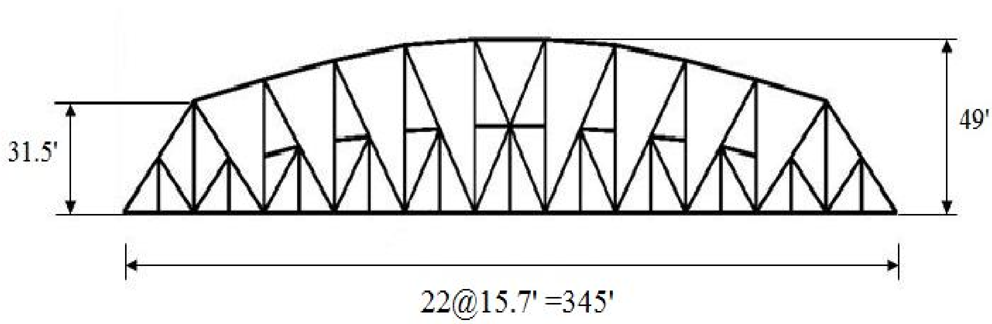

Figure 1. Side view of Hardinge Bridge.

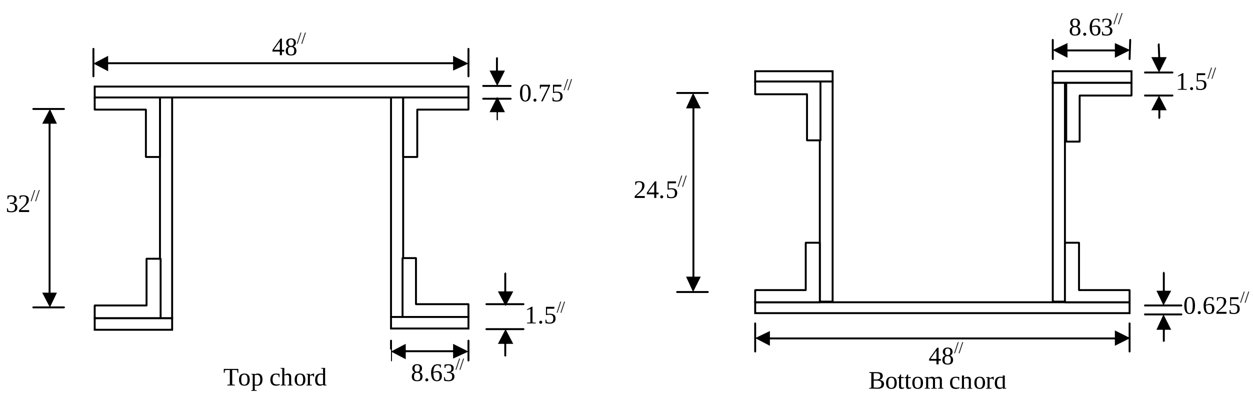

Figure 2. Cross sectional details of top chord and bottom chord of Hardinge bridge

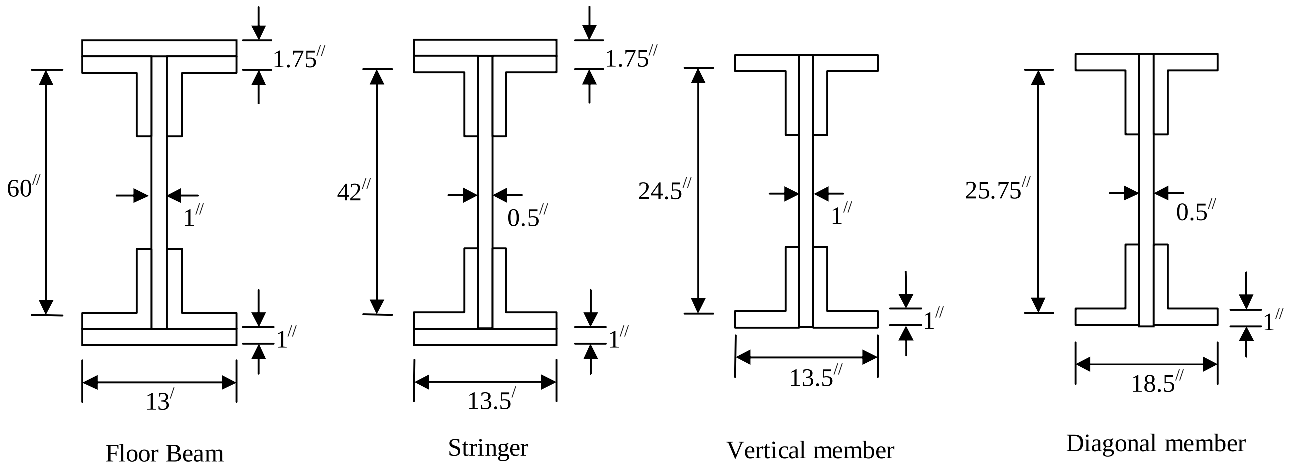

Figure 3. Cross sectional details of different members of Hardinge Bridge.

Hardinge bridge is made up of prefabricated steel and all the joints of this bridge are riveted joints. All members are fabricated by combined plates and angles. Top chord and bottom chord is box shaped which is the combination of several plates and angles. Cross sectional details of top chord and bottom chord is shown in Figure 2. Floor Beam, stringer, vertical and diagonal members all are also riveted joints and consists of plates and angles shown in Figure 3.

2.2 *Loads on Hardinge Bridge*

In this paper dead load and live load are considered for the analysis. The dead load includes the self weight of the bridge members and all other superimposed loads which are permanently attach to the structure. There are two railroads in the bridge and the weight of rails and sleepers are taken as 0.09 kip/ft as uniformly distributed load along the four stringers of the bridge (Gupta & Gupta, 2003).

Live load is considered as train load. For this reason wheel arrangement and loading of WDM2 Co-Co type for locomotive and Bo-Bo type for bogies are considered. For both types wheel load is 21 kips. Center to center distance between two wheels of Co-Co type locomotive and Bo-Bo type bogies are 6.75 feet and 8.5 feet respectively (Scannel *et al.* 2011). Figure 4 shows the wheel arrangement and loading of Co-Co type locomotive and Bo-Bo type bogies.

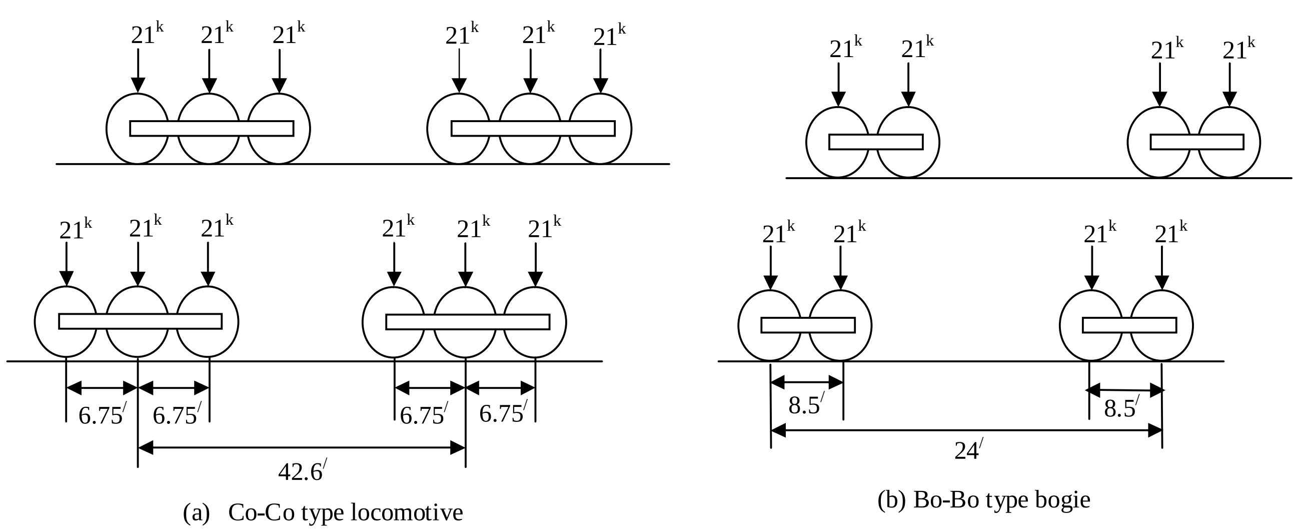

Figure 4. Wheel arrangement and loading of (a) Co-Co type locomotive and (b) Bo-Bo type bogie

2.3 *Modeling of Hardinge Bridge*

Modeling of Hardinge Bridge is carried out by commercially available STAAD.Pro software. The commercial version of this software is one of the most widely used structural analysis and design software. At first the framework of the bridge is modeled by generating nodes and connecting those nodes. Considering simply supported span, and roller and hinge supports are provided to the model. Then the property of the bridge is assigned to the whole framework. Cross section of different members are provided through the built in user table option of this software. Figure 5 shows the isometric view of Hardinge Bridge.

After that, dead loads and live loads are applied to the bridge model. Dead load contains self weight and superimposed load. In software self weight is automatically assigned in the whole body of the structure but superimposed load is assigned as uniformly distributed load along the four middle stringers of the bridge. Train load is applied as live load; therefore, loading conditions of WDM2 Co-Co type locomotive and Bo-Bo type bogies are created through vehicle definition in software. This train load is applied on bridge after one feet interval. Figure 6 shows the moving load application on Hardinge Bridge model. Where first two sets load represent the locomotive loading and preceding each two sets represent the bogies loading.

2.4 *Comparison of Axial Stresses Between Intact And Fractured Conditions*

After modeling and application of loads on the bridge the whole span is analyzed in intact condition. Axial stresses of different members can be directly calculated by the software. Then one primary member is removed from the model considering that member is fractured and the analysis is performed again. Axial stresses of different members in fractured condition are calculated and compared with intact condition. In this paper three important fractured conditions in different locations are described.

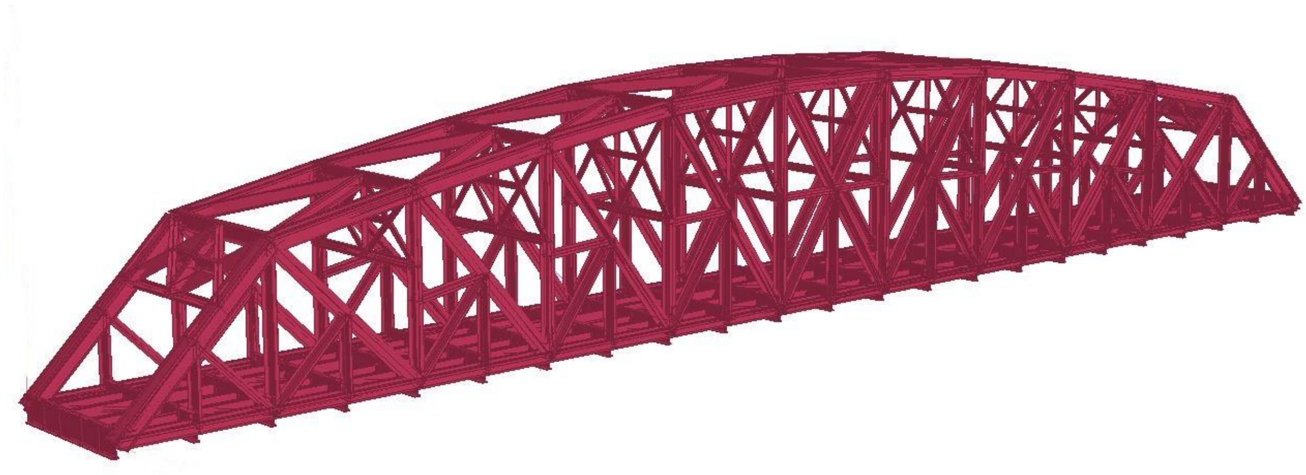

Figure 5. Isometric view of Hardinge Bridge modeled by STAAD.Pro software.

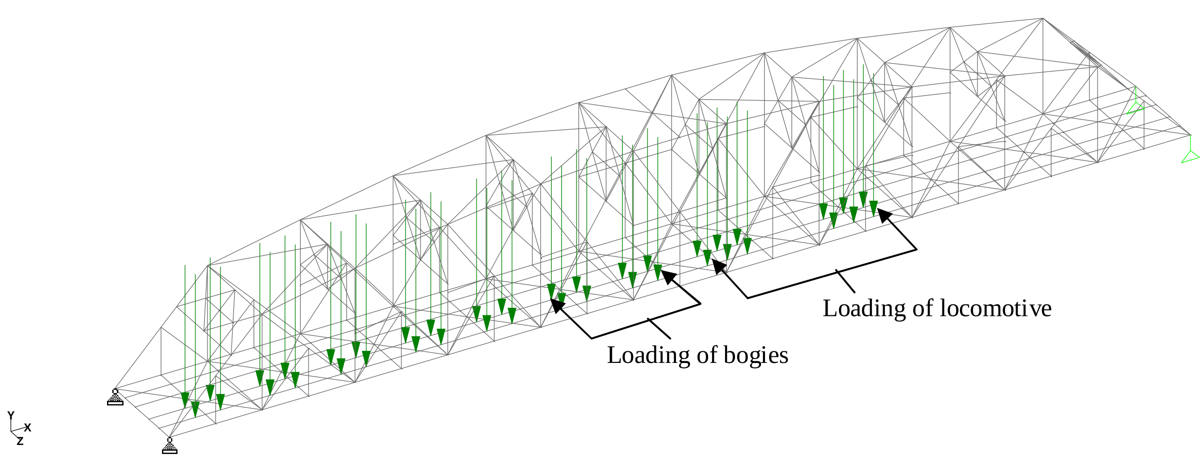

Figure 6. Moving load application on bridge model.

2.4.1 *Fracture of vertical member (c)*

In first condition, vertical member (c) is considered as fractured member. Figure 7 shows the fractured vertical member representing as a dotted line and its adjacent members. From Figure 7 it is seen that member (d) will not carry any force for the fracture of member (c), as it is directly connected with the fractured member (c).

Table 1 represents the axial stresses of adjacent members (a), (b) and (e) before and after fracture condition. This table shows the percentage of increase and decrease of axial stress for dead load, moving load and combined load case conditions separately. From the analysis it is seen that for the fracture of vertical member (c), axial stress of member (b) is increased around 78% for only dead load case and around 66% for combined load case. This is because of members (c), (b), (e) and (d) simultaneously formed a single truss unit and when member (c) is damaged the truss unit becomes unbalanced. Member (d) will also act as dummy member as it is directly attached with the fractured vertical member. As a result 66% load is increased in member (b). If this extra load exceeds the load carrying capacity of the member (b), this member will also fail and the bridge will progressively collapse.

2.4.2 *Fracture of vertical member (h)*

In this condition, vertical member (h) is taken as fractured member and here also member (i) will not carry any force as it is attached directly with the member (h). Figure 8 shows the fractured vertical member and its adjacent members.

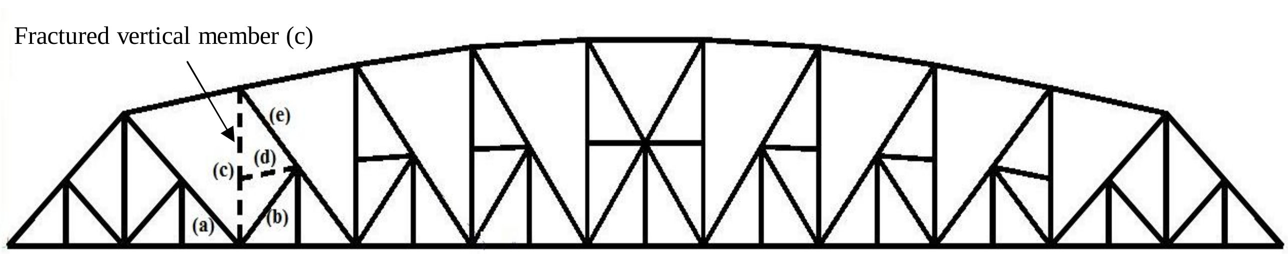

Figure 7. Fractured vertical member (c) and its adjacent members.

Table 1. Axial stresses of adjacent members due to fracture of vertical member (c)

Member	Dead load			Moving load			Combined load (Dead load + Moving load)		
	Stress before fracture (psi)	Stress after fracture (psi)	Percent	Stress before fracture (psi)	Stress after fracture (psi)	Percent	Stress before fracture (psi)	Stress after fracture (psi)	Percent
(a)	-7994.09	-7263.22	Decrease 9.14%	-6440.22	-5963.19	Decrease 7.4%	-14434.3	-13226.4	Decrease 8.37%
(b)	1416.44	2530.34	Increase 78.64%	1593.97	2488.02	Increase 56.08%	3010.41	5018.36	Increase 66.70%
(e)	-4894.63	-3442.34	Decrease 29.67%	-4677.11	-3503.50	Decrease 25.09%	-9571.74	-6945.84	Decrease 27.43%

Fractured vertical member (h)

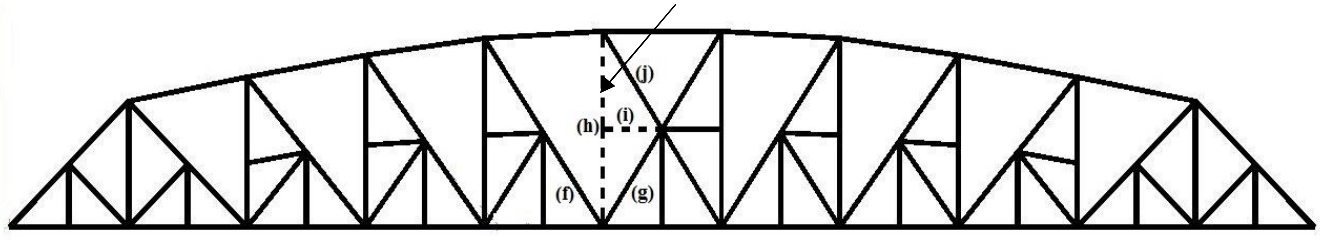

Figure 8. Fractured vertical member (h) and its adjacent members.

Table 2. Axial stresses of adjacent members due to fracture of vertical member (h)

Member	Dead load			Moving load			Combined load (Dead load + Moving load)		
	Stress before fracture (psi)	Stress after fracture (psi)	Percent	Stress before fracture (psi)	Stress after fracture (psi)	Percent	Stress before fracture (psi)	Stress after fracture (psi)	Percent
(f)	-1585.40	-1596.54	Increase 0.70%	-3735.49	-3714.32	Decrease 0.57%	-5320.89	-5310.84	Decrease 0.19%
(g)	215.82	-144.87	Decrease 32.87%	2258.96	-4071.62	Increase 80.24%	2474.78	-4215.62	Increase 70.34%
(j)	-2016.38	-1474.69	Decrease 26.86%	-4093.85	-2980.25	Decrease 27.20%	-6110.23	-4454.94	Decrease 27.09%

Table 2 represents the axial stresses of adjacent members (f), (g) and (j) before and after fracture condition. This table shows the percentage of increase and decrease of axial stresses for dead load, moving load and combined load cases separately. From the analysis, it is seen that for the fracture of vertical member (h) axial stress of member (g) is increased around 70%. This is because member (h), (g), (j) and (i) simultaneously formed a single truss unit and when member (h) is damaged the truss unit becomes unbalanced. Member (i) will also act as dummy member as it is directly attached with the fractured vertical member (h). As a result 70% load is increased in member (g). If this extra load exceeds the load carrying capacity of the member (g), this member will also fail and the bridge will progressively collapse.

2.4.3 *Fracture of diagonal member (k)*

In this condition, the fracture of diagonal member (k) is considered and comparison of axial stresses between intact and fractured conditions is described. Figure 9 shows the fractured diagonal member and its adjacent members. Dotted lines represent the inactive member.

Table 3 represents the axial stresses of adjacent members (l), (o) and (p) before and after fracture of diagonal member (k). This table shows the percentage of increase and decrease of axial stresses for dead load, moving load and combined load cases separately. From the analysis, it is seen that for the fracture of diagonal member (k), axial stress of member (l) is increased drastically around 210% for only dead load case and around 158% for combined load case. This is because members (k), (l), (m) and (n) simultaneously formed a single truss unit and when member (k) is damaged the truss unit becomes unbalanced. Member (m) and (n) will also act as dummy members as they are directly attached with the fractured diagonal member. As a result 158% load is increased in member (l). If this extra load exceeds the load carrying capacity of the member (l), this member will also fail and the bridge will collapse progressively.

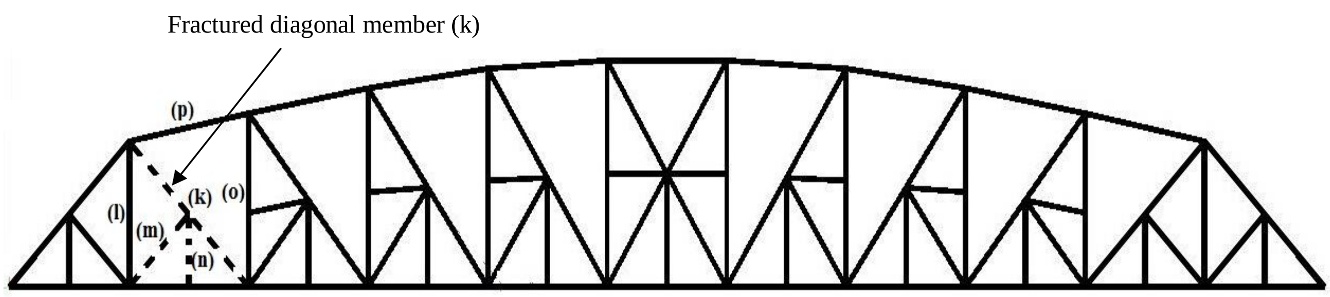

Figure 9. Fractured diagonal member (k) and its adjacent members.

Table 3. Axial stresses of adjacent members due to fracture of diagonal member (k)

Member	Dead load			Moving load			Combined load (Dead load + Moving load)		
	Stress before fracture (psi)	Stress after fracture (psi)	Percent	Stress before fracture (psi)	Stress after fracture (psi)	Percent	Stress before fracture (psi)	Stress after fracture (psi)	Percent
(l)	-1874.15	-5814.07	Increase 210.22%	-2954.11	-6652.75	Increase 125.20%	-4828.26	-12466.8	Increase 158.19%
(o)	5426.25	2930.09	Decrease 46%	4671.52	3074.01	Decrease 34.2%	10097.7	6004.1	Decrease 40.54%
(p)	7879.44	5450.06	Decrease 32.48%	5671.22	3924.22	Decrease 30.80%	13550.6	9374.28	Decrease 30.82%

3 CONCLUSIONS

The redundancy analysis of truss bridges is a complex process that requires an exhaustive investigation in order to characterize all possible damage scenarios and the response of the bridge under different loading conditions.

In this paper redundancy is described with respect to change in axial stresses before and after fracture of different members. From this analysis it is seen that increase of axial stress varying with different damage scenario. Fracture of diagonal member (k) drastically increased the axial stress of one of its adjacent member. So it can be taken as critical fracture member that means failure of this member lead the bridge progressively collapsed. Vertical members (c) and (h) could be critical also if proper maintenance is not carried out and if train speed and loading is not strictly regulated. As the service life of Hardinge Bridge is almost 100 years; therefore as an old steel bridge, frequent inspection and proper maintenance is very essential to avoid unpredictable catastrophe.

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