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Experimental investigations on the structural behaviour of a distressed bridge

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Abstract. Distressed structures require necessary remedial measures in order to restore their original structural properties like strength and stiffness. Validating the effectiveness of the proposed qualitative remedial measure experimentally is of utmost importance as there is no well-established analytical method to verify the effectiveness of the same quantitatively. Prototype testing which would have been the best option for this purpose would not only prove costly but also be associated with numerous practical difficulties; hence model testing is resorted as the only option for the purpose. This paper presents one such typical experimental study on the structural behavior of a distressed bridge, mainly observed in the form of prominent tilt in the bearing plate in transverse and longitudinal direction on downstream side. The main focus of the proposed experimental investigation is to assess the structural behavior particularly the load carrying capacity. The extent of deformation of some models with specific structural arrangements and some models with specific need based remedial measures were also studied. This study also assessed the contribution of each remedial measure towards restoration individually and collectively.

Keywords: truss girder bridge; pipe rack; severe distress; bearing plate; remedial measures

1. Introduction

In the year 2008, a contract for laying 700 mm diameter water supply pipeline project from water treatment plant situated at Rangil, Ganderbal to Shalteng area of Srinagar (Jammu & Kashmir, India) city was won by Pratibha Industries Ltd Mumbai. Along its alignment, the pipeline had to cross the largest river in Kashmir Valley called Jehlum (150 m wide) at Palpora located in the outskirts of Srinagar. A pipe rack was constructed to carry this water supply pipe (diameter 700 mm) across the Jehlum river. The super structure of pipe rack is arch shaped truss girder bridge consisting of four equal spans of 37.5 m each as shown in Fig. 1. Due to limited available time for the completion of the project, the fabrication work of truss girders was carried out in Jalandhar (Punjab) in parallel with the execution of sub structure works to ensure timely completion.

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Fig. 1 A view of four span Pipe Bridge

Fig. 2 A visible tilt in the bearing plate

Fig. 3 Eccentric placement of cross girder over the bearing plate

2. Problem statement

Due to lack of proper coordination between site and fabrication teams, the length of each span of the truss was fabricated 37 m only instead of the desired 37.5 m. Miserably inadequate non engineered measures were taken at site to make up for the deficiency in the desired span length. These non-engineered measures included the improper arrangement of bottom chord extension, highly insufficient channel section for top chord extension together with unsafe joint detailing. This totally non-engineered approach finally resulted in a structurally unsafe solution to the above quoted crucial problem of the structure. The proposed restoration scheme suitable for a structure in distress is governed by the nature and extent of distress the structure has undergone (Jagadish 1995, Limal *et al.* 2008, Peterson 2011, Edward *et al*. 2014). Before selecting the suitable and acceptable restoration scheme, it is important to critically examine the nature and extent of distress the structure has suffered (Arya *et al*. 1992, Mehta 2010, AASHTO 2011, Caglayan *et al*. 2012, Stamatopoulos 2013, Subramanian 2014). At times, it is also the imposed constraints from various considerations which play important role in the selection of suitable restoration scheme (Goel and Sanyal 1999, Ram Kumar *et al.*1999, Williams 2013, Subramanian 2014). To explore the various alternative restoration schemes for the distressed pipe rack in the present study, it was necessary to examine critically the nature and extent of distress. For this purpose few visits were paid to the site at a time when signs of distress were clearly noticeable as well as fabrication faults and errors were also visible. The distress in the pipe rack was observed in the form of noticeable tilt in one of the bearings and significant tilt in the girder supported by this bearing, as is clearly seen in Fig. 2. It was also observed that the end cross girders in all the spans were located about 250 mm away from the centre line of the bearings towards the river side, as seen in Fig. 3. In addition to this a prominent tilt measuring 1 in 9 in transverse direction and 1 in 45 in longitudinal direction was observed on the down-stream side of bearing in span 3 over Pier P3 as shown in Fig. 2. Wide gaps were also observed at number of joints as well as non-uniform gaps were visible at expansion joints. The newly constructed pipe rack was thus severely in distress. The pipe rack in such distressed condition was vulnerable to total collapse particularly under seismic loading of zone-V, resulting in the disruption of essential water supply service to millions of people across the river. Considering its vital importance, an urgent need was felt to take appropriate remedial measures of the distressed pipe rack to restore its safe structural capacity particularly during worst seismic loading condition in zone-V.

3. Methodology followed

For validating the effectiveness of any proposed remedial measure, it will be essential to have desired benchmark of relevant parameters of this bridge. Accordingly, fabrication of the perfect truss bridge (without any fabrication fault) will be required for detailed testing so that the load carrying capacity and the structural behavior may be assessed in order to provide the necessary bench mark parameters both in numerical and graphical form for comparison. It was equally important to assess the reduction in both load carrying capacity and flexural stiffness caused by adopting the inadequate non-engineered remedial measures by the locally engaged inexperienced fabricator. Therefore, fabrication of the Prototype truss bridge (having close simulation of fabrication fault) will be required for detailed testing to assess the structural deficiencies in terms of the desired parameters.

The various remedial measures proposed have their individual contribution towards restoration. Therefore fabrication of Prototype truss bridge strengthened with the Remedial Measure-1, Remedial Measure-2 and then the combination of both Remedial Measure-1 and Remedial Measure-2 will be required for detailed testing to assess the levels of restoration contributed by each respectively.

Remedial Measure-1 includes addition of one more cross beam at the ends which is placed centrally over the bearings and properly made with sound connection details so that the two cross beams act as one built-up beam in order that the load transfer through this mechanism is at the ends and finally to the bearings as centrally as possible (Subramanian 2008).

Remedial Measure -2 includes the adequate extension of top chord and bottom chord members with appropriate connection details so that the extension part acts as an integral part of the pipe-rack, thus making the structure act as a truss (Schodek 2000, Hatfield 2001, Clark *et al*. 2006, Hibbeler 2008).

The enhancement in maximum load carrying capacity by each remedial measure is to be rationalized in order to quantify the percentage recovery by each measure independently and jointly. This will help in evaluating the effectiveness of the proposed remedial measures.

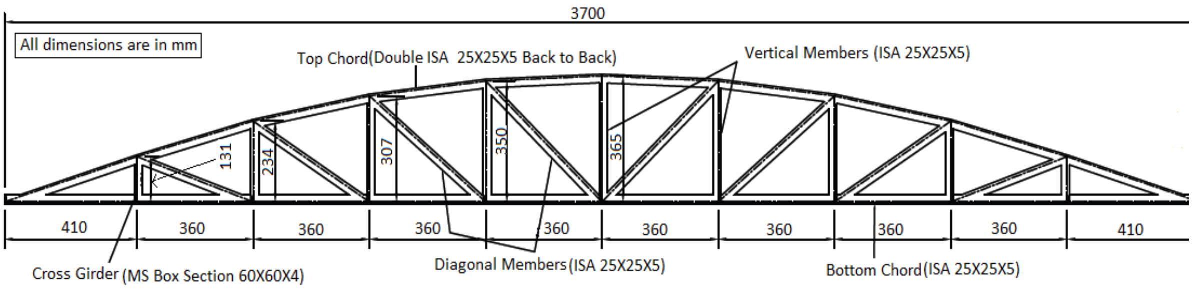

Fig. 4 Detailed figure of the bridge model

Table 1 Material properties of steel used

Grade of steel	Unit weight of steel	Modulus of Elasticity	Yield strength	Ultimate strength	Minimum percentage elongation	Poisson's ratio
Standard structural steel (Fe-410)	7850 kg/m^3	2×10^5 MPa	250 MPa	410 MPa	23%	0.3

4. Model analysis for fabrication of scaled models

In professional structural design practice sometimes situations arise which are not amenable to theoretical analysis. Under such circumstances it is necessary to use experimental techniques which are mostly conducted on scale models and rarely on prototype structures. There has to be close similarities between the response of scaled model with the response of prototype structure (Ganesan 2005). Since in the present project, the purpose of scale model testing was to validate the effectiveness of proposed remedial measures for restoration of distressed pipe rack rather than the replication of the response of actual pipe rack. Furthermore, the scaled model size was governed by the loading frame and other testing related facilities available in the laboratory. Therefore, a classical model analysis was not resorted to and the size of the model was mainly fixed as per the available facilities in the structural model testing laboratory of the department. Accordingly 1:10 scaled model which resembles prototype in geometry was considered for design and fabrication of various bridge models. The various geometrical dimensions of the bridge model along with member details are shown in Fig. 4. The relevant material properties of the steel used are given in Table 1. For connection of members at joints 5mm fillet weld was used.

5. Evaluation of experimental set-up

Before carrying out the serious experimental work for achieving the defined objectives, it is essential to critically evaluate the performance of the experimental set-up being used for the purpose. This is necessary to have confidence on the accuracy and reliability of experimentally measured data. For checking the performance of the experimental set-up, the best courses of action is to perform preliminary testing on a trial model as shown in Fig. 5. This would not only help in checking the performance of loading frame but will also help in identifying the shortcomings (if any) in the trial model and will provide clues to make necessary changes in the bridge models (if required) for obtaining better results from the experimental testing. The bridge models were tested

Fig. 5 Experimental setup and preliminary model under performance evaluation

on a 500 kN loading frame as shown in Fig. 5. The loading was applied symmetrically at two points on the span through a spreader rigid beam which was loaded centrally by the ram of the 500kN capacity hydraulic loading jack. All the tests were conducted with symmetric loading points at a distance of two fifth of the span from the supports. A proving ring of 200 kN capacity was mounted between the loading jack and frame as shown in Fig. 5 to record the load applied.

6. Detailed experimental testing of models and data recording

Having identified the improvements required in model fabrication as well as selection of safe and satisfactory arrangement for load transfer through preliminary testing, a set of five different bridge models were selected for testing. These five bridge models have to be fabricated with specific variations (i.e., simulating the corresponding prototype conditions) and tested to obtain appropriate experimental data for necessary data analysis and interpretation of results. These five different models are: Perfect (bridge model with desired span as per support spacing), RM 1 (model with remedial measure I), RM 2 (model with remedial measure 2), RM 1+RM 2 (model having combined remedial measure 1 and 2), and Prototype (model with structurally inadequate extension at both ends).

7. Data analysis and observations

The experimental data recorded during testing of five different bridge models with specific variations in their structural conditions needs to be analyzed to facilitate the meaningful interpretation of the experimental results. This will be followed by necessary interpretation and discussion about the experimental results. Graphical representation of load v/s deflection data is helpful to get physical feel about the structural response to applied loading. Such a data recorded in tabular form is not of much help, therefore, is transformed in graphical from. The important observations and salient points worth noting will also be presented here. Fig. 6 shows typical load

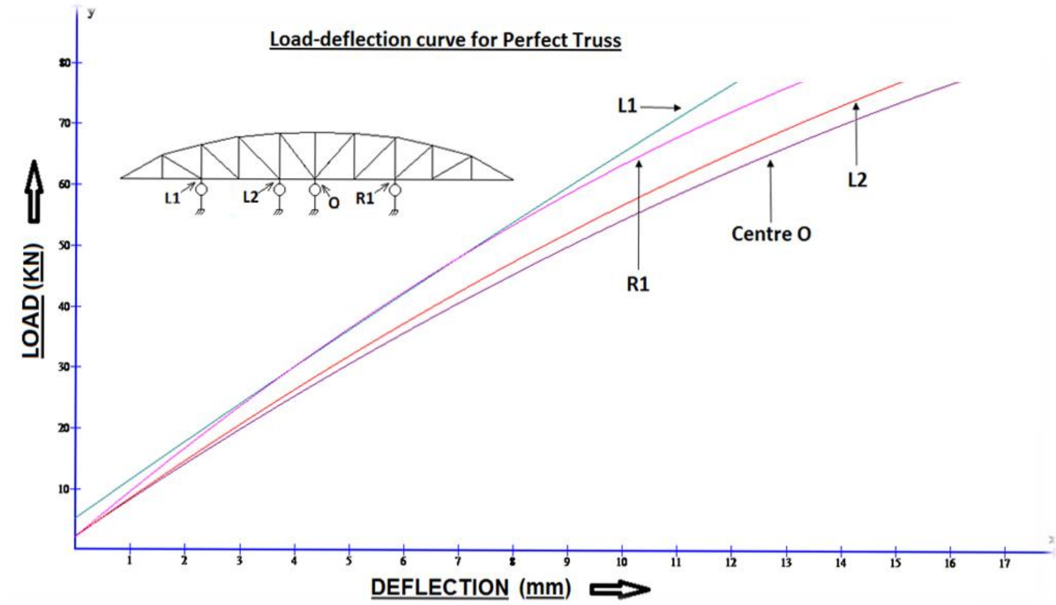

Fig. 6 Load deflection graph of perfect truss

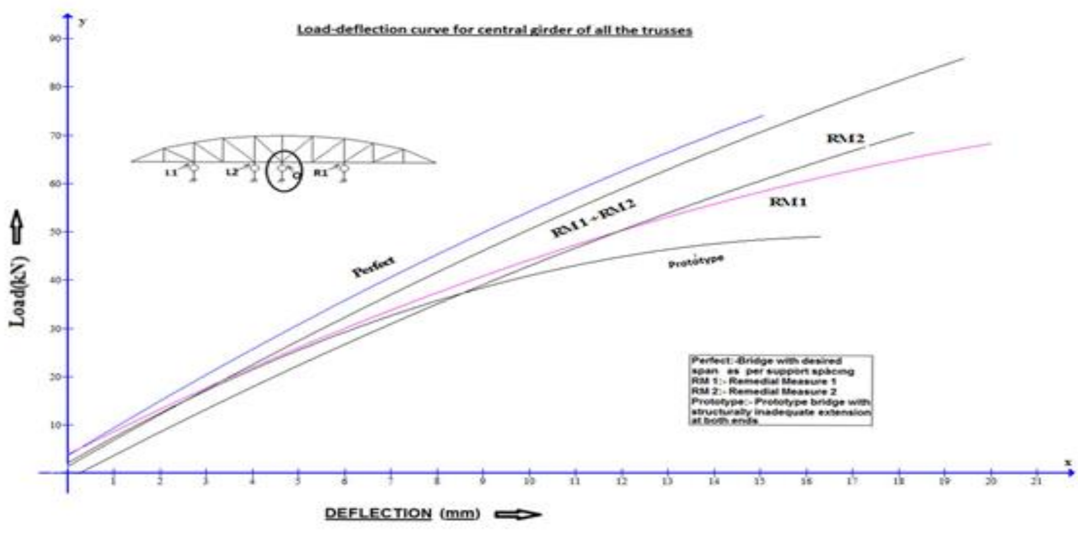

Fig. 7 Load deflection curve of 5 models at central location, O

displacement plots at the specified nodes for the perfect truss. Similar graphs were obtained for the remaining models too.

7.1 Load-displacement plot of all five models on a single graph

For better comparison as well as to get a physical feel of variations in structural response governed by the specific structural condition of each model, it would be interesting to plot load displacement curves of all the five different models on a single graph.

Fig. 7 shows the graphical plot of load Vs. deflection measured at central locations of all the five models.

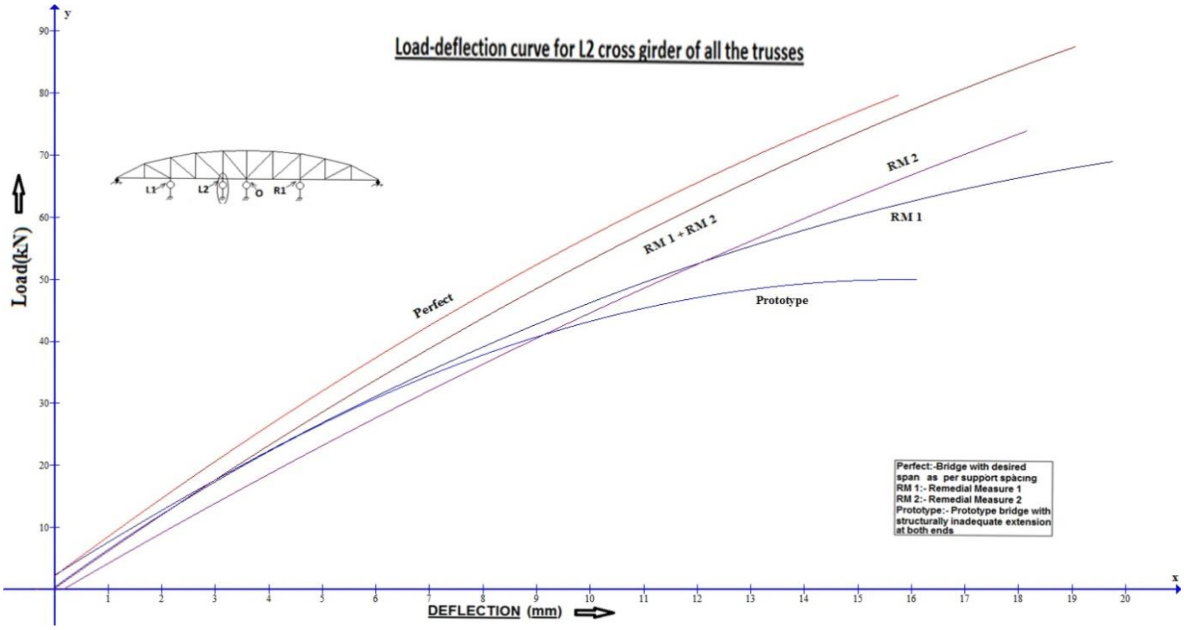

Fig. 8 Load deflection curve of 5 models at L2 location

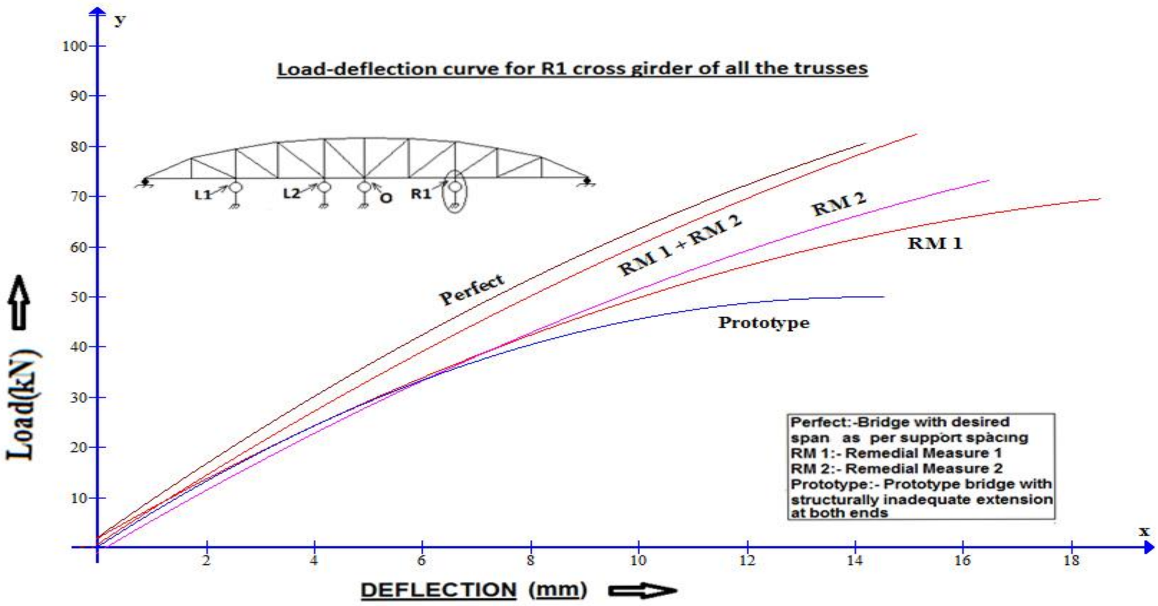

Fig. 9 Load deflection curve of 5 models at R1 Location

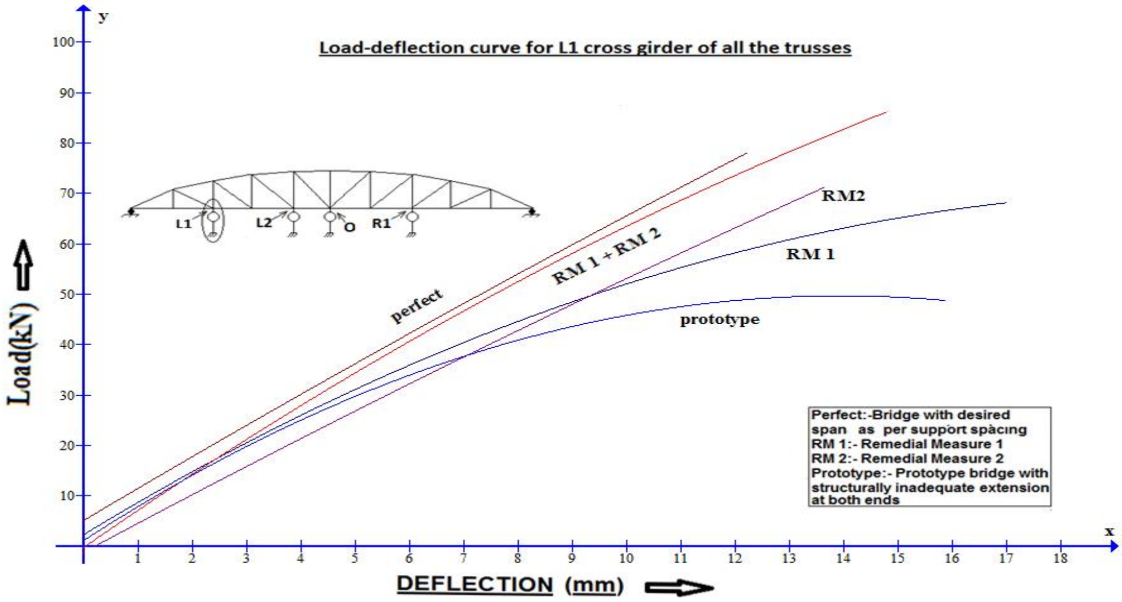

Fig. 10 Load deflection curve of 5 models at L1 location

7.2 Observations

The curve corresponding to perfect model, as expected, is at the top indicating the highest carrying capacity whereas the curve corresponding to distressed model shows the lowest capacity thus confirming the structural degradation caused by improper rectification of the fabrication fault.

Curves corresponding to distressed models rectified with remedial measures RM-1 and RM-2 respectively are higher than distressed model and shows significant structural recovery contributed by each remedial measure taken individually. The curve corresponding to distressed models rectified with combined remedial measure RM-1 and RM-2, as expected, is much higher than the curves for individual models rectified with RM-1 & RM-2 individually and are very close to the curve corresponding to perfect truss. This confirms that the level of recovery achieved by combined remedial measures RM-1 & RM-2 is very encouraging and satisfactory as per the desired target.

Figs. 8, 9 & 10 show similar graphical plots of load v/s deflection corresponding to three other locations for all the five models and results in all the three graphs reflecting identical trend, thus supporting the interpretation of the results based on Fig. 10 discussed above.

The above experimental results validate the behavior of the proposed remedial measures and shows that the combined remedial measure RM-1 + RM-2, provides the best means of rectification to achieve the acceptable level of rehabilitation to the distressed pipe rack.

8. Result interpretation & discussion

The discussion of the experimental results till now reflects qualitatively the recovery towards the desired structural condition by adopting the various remedial measures. It will be interesting to

Table 2 Load carrying capacity trend

Particulars of model	Maximum failure load (kN)	Maximum deflection measured at locations (mm)			
		Centre	L2	R1	L1
Perfect Model	76	16.24	15.45	13.13	11.65
Distressed Model with RM1 + RM2	74	19.55	17.88	14.71	14.26
Distressed Model with RM2	70	18.16	17.08	16.11	13.16
Distressed Model with RM1	68	20.10	19.16	17.96	16.69
Distressed Model	50	17.94	17.50	16.73	16.33

Fig. 11 Remedial Measure-I Implemented in real (i.e., as buit) pipe-rack

Fig. 12 Remedial Measure-II Implemented in real (i.e., as built) pipe-rack

express the said qualitative results in quantitative form for meaningful interpretation. The failure loads of all the models in consolidated form are given in Table 2 which clearly indicates that the load carrying capacity decreases in the following order:

Perfect Model > (RM-1+RM-2) > RM-2 > RM-1 >> Distressed Model

Degradation of distressed model in terms of load carrying capacity = (76-50)/76 =34.2%
Recovery achieved through remedial measure 1 (RM-1) alone =23.6%
Recovery achieved through remedial measure -2 (RM-2) alone =26.3%
Recovery achieved through combined remedial measure 1 & 2 (RM-1+RM-2) =31.5%
This is very close to desired recovery of 34.21%, hence falling within acceptable limits.

This confirms that combined remedial measure 1 & 2 (i.e., RM-1+RM-2) help in recovering the loss in strength due to the distressed condition almost to the required level, hence validates the effectiveness of proposed combined remedial measure for the distressed pipe rack quantitatively.

The above experimentally validated remedial measures were applied to the real distressed pipe-rack with high degree of confidence. Fig. 11 shows implementation of remedial measure 1 i.e., addition of another cross beam at the ends to ensure load transfer at bearings as centrally as possible. Fig. 12 shows implementation of remedial measure 2 i.e., adequate extension of top chord and bottom chord members to ensure that extension part acts as an integral part of the pipe-rack, thus making the structure to act as a truss. Since the total weight of the additional steel sections used for restoration is a very small fraction of the total weight of the bridge, thus will have negligible effect on the seismic response of the bridge.

9. Conclusions

Restoration measures are possible for rehabilitation of structures which undergo structural distress on account of faulty construction/fabrication. However, restoration measures proposed for any distressed structure are dependent on numerous factors like, the nature and extent of distress, constraints for implementation of proposed measures, etc. Hence it is not possible to develop any design method for such a complex situation. The restoration measures proposed are, therefore, mainly governed by engineering judgment of a structural engineer rather than by any design method. Once remedial measures are decided on engineering judgment, they are qualitative in nature, thus bound to have high degree of uncertainty so far as their desired effectiveness is concerned. Considering the above difficulties in restoring the original structural capacity of any distressed structure, utmost care must be taken during construction/fabrication so that any chance of such a structural distress is avoided in the first place, especially in case of structures of great importance, like pipe rack carrying essential water supply service and other structures of similar importance. Before implementing the need based qualitative remedial measures, it is important to have their quantitative assessment with high precision experimentation.

The results obtained from the present experimental study on a bridge structure were found very promising and have validated the proposed remedial measures. They also showed that the restoration of the original structural to a desired level is possible and thus making the important pipe rack bridge structurally safe.

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