Structural Engineering and Mechanics, *Vol. 62, No. 5 (2017) 567-576*
DOI: https://doi.org/10.12989/sem.2017.62.5.567

Rehabilitation of a distressed steel roof truss - A study

M.A. Dar*[1], N. Subramanian[2], A.R. Dar[3] and J. Raju[1]

[1]*Department of Civil Engineering, MSRIT, Bangalore, India*
[2]*Consuting Engineer, Maryland, USA*
[3]*Department of Civil Engineering, NIT Srinagar, J&K, India*

(Received December 28, 2016, Revised March 28, 2017, Accepted March 29, 2017)

Abstract. Structural failures are undesirable events that devastate the construction industry resulting in loss of life, injury, huge property loss, and also affect the economy of the region. Roof truss failures occur mainly due to excessive loading, improper fabrication, deterioration, inadequate repair, etc. Although very rare, a roof truss may even fail due to inappropriate location of supports. One such case was reported from the recent failure of a steel roof truss used in an indoor stadium at Kargil in India. Kargil region, being mountainous in nature, receives heavy snowfall and hence the steel roof trusses are designed for heavy snow loads. Due to inappropriate support location, the indoor stadium's steel roof truss had failed under heavy snow load for which it was designed and became an interesting structural engineering problem. The failure observed was primarily in terms of yielding of the bottom chord under the supports, leading to partial collapse of the roof truss. This paper summarizes the results of laboratory tests and analytical studies that focused on the validation of the proposed remedial measure for rehabilitating this distressed steel roof truss. The study presents the evaluation of (i) significant reduction in strength and stiffness of the distressed truss resulting in its failure, (ii) desired recovery in both strength and stiffness of the rectified truss contributed by the proposed remedial measure. Three types of models i.e., ideal truss model, as build truss model and rectified truss model were fabricated and tested under monotonic loading. The structural configuration and support condition varied in all the three models to represent the ideal truss, distressed truss and the rectified truss. To verify the accuracy of the experimental results, an analytical study was carried out and the results of this analytical study are compared with the experimental ones.

Keywords: faulty fabrication; rehabilitation; steel truss; distress; remedial measure

1. Introduction

Infrastructure plays a key role in the development and prosperity of any nation. Structural failures are undesirable happenings that must be avoided in all forms, especially considering the two main global challenges i.e., increasing population and limited reserves of construction materials. Roof trusses are generally made up of timber or steel. Cold formed steel C and Z sections are often used as purlins in steel roof trusses (Anbarasu 2016). Although timber trusses have been traditionally used for centuries, they fail to meet some necessary requirements such as in small span trusses with raised king-post (Munafò *et al*. 2015), resistance against deterioration of joints (Abramyana and Ishmametova 2016, Foo 1993, Branco 2010), discontinuity of rafter beyond the point of intersection in the tie beam (Barbari *et al*. 2014), absence of high strength to weight ratio for longer life (Dawe *et al*. 2010) and need of strengthening by metal bracing (Burdzik and Skorpen 2014). Steel trusses even though stronger than timber trusses might fail if not designed and fabricated properly (Jagadish 1995, Piroglu and Ozakgul 2016) or even under unforeseen meteorological events (Piroglu *et al*. 2014). Therefore proper structural designing followed by quality fabrication is necessary for preventing such failures.

In the year 2012, a project of constructing an indoor stadium was taken up by the Roads and Buildings Division in the city of Drass at Kargil. This stadium was constructed for conducting indoor sports such as Table Tennis, Badminton and Basket Ball. The main building of the stadium was an RC framed structure with brick masonry as infill walls. Keeping in view the heavy snowfall in the region during the winter months (i.e., October to April), the roof was made of steel trusses and designed for heavy snow loading. However, due to faulty structural design followed by poor quality of fabrication, the bottom chord of the truss yielded near the supports leading to partial collapse under heavy snow load (Load it was designed for) as shown in Fig. 1 and Fig. 2. The overhang portion (Chajja) had failed completely. This failure clearly demonstrated the deficit in the design and poor execution. The truss action was rendered ineffectively, making it to behave like a flexural member rather than an axially loaded member (Hibbler 2008, Schodek 2000). While examining the failure, it was assessed that inappropriate support position was the main cause for this complete failure. There was not an imbricate in the position of wall support and support node of the truss. In a roof truss the loads act on the top chord through purlins. This load gets transferred to the bearing point through webs and bottom chord as shown in Fig. 3. The placement of supports plays a vital role in trusses as its

*Corresponding author, Former BE Student
E-mail: dar.adil89@gmail.com

http://www.techno-press.com/journals/sem&subpage=7
ISSN: 1225-4568 (Print), 1598-6217 (Online)

components are designed to resist axial loads only. In case of improper placement of supports, the behaviour of the bottom chord may change from tension member to a flexural member as shown in Fig. 4. The bottom chord originally designed for tensile forces may not be adequate to withstand flexure and may result in failure of the truss by yielding of bottom chord at the support as shown in Fig. 5.

Keeping in view the size of the truss and slow construction progress (because of limited working season available on account of long and very harsh winter), there was an impelling need to propose an appropriate remedial measure that would rectify this distressed truss with least material losses. From value engineering consideration, dismantling the whole truss configuration is not an engineer's solution (Subramanian 2014a, b). Proper rehabilitation should be carried out i.e., replacement of failed truss members while rest of the truss remains undisturbed (Dar *et al*. 2015, Subramanian 1998, 2014a). Since remedial measures proposed are based on engineering judgment and being qualitative in nature, they are bound to have high degree of uncertainty so far as their desired effectiveness is concerned. To overcome this uncertainty, the validation of the proposed remedial measure, particularly through physical testing of scaled model trusses will be most appropriate.

The validation of the proposed remedial measure for rehabilitating this distressed steel roof truss is discussed in this paper. This study was done in three steps. First, an experimental program on three types of models were conducted i.e., ideal truss model, as built truss model and rectified truss model under monotonic loading. The structural configuration and support condition is varied in all the three models to represent the ideal truss, distressed truss and the rectified truss. The reduction in strength and stiffness in the distressed truss model with respect to desired truss model is quantified. After implementing the remedial measure, the recovery in both strength and stiffness is again quantified. Second, an analytical study was carried out at failure loads in all the models using STAAD Pro V8i. Comparison is made between the test results and the predictions based on STAAD Pro V8i analysis. Lastly, a parametric study was carried out on different sizes of sections in the proposed remedial measure for material optimization.

2. Methodology followed

For validating the effectiveness of the proposed remedial measure, it was essential to have desired benchmark of relevant parameters. Accordingly, fabrication of a model without any fabrication fault will be required for detailed testing to evaluate the load carrying capacity and the structural behavior. This will provide the necessary benchmark parameters both in numerical and graphical form for comparison. This model is named as ideal truss model and is shown in Fig. 6. For future references this model is referred to as ITM (Ideal Truss Model).

It is important to determine the reduction both in the load carrying capacity and in stiffness of the truss due to improper support location. Therefore, fabrication of a model having close simulation with the inappropriate support locations will be required for detailed testing and to find its load carrying capacity and stiffness. This model is named as 'as built truss model' and is shown in Fig. 7. For future references this model is referred to as BTM (as Built Truss Model).


Fig. 1 Failure of Roof Truss at Kargil


Fig. 2 A view of yielded bottom chord near the support

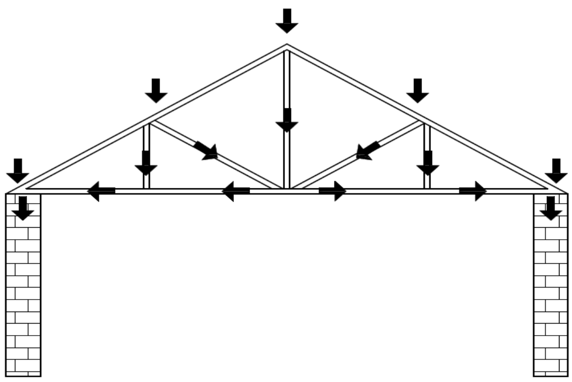
Fig. 3 Load path in a truss

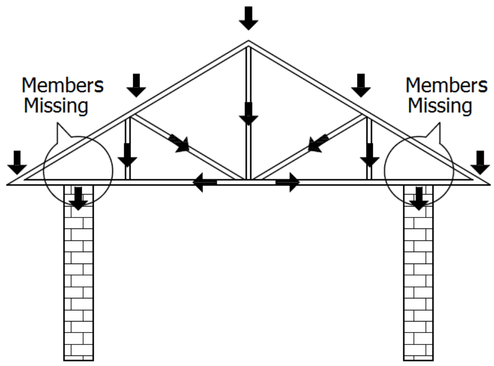

Fig. 4 Load path in a truss with improper support location

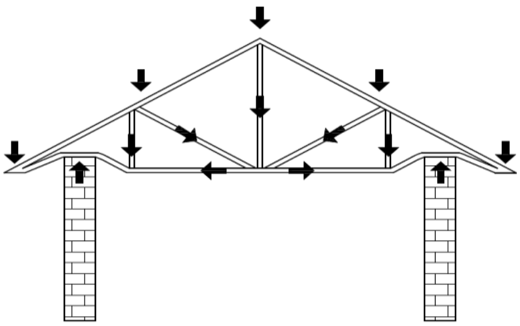

Fig. 5 Yielding of bottom chord under heavy snow loading

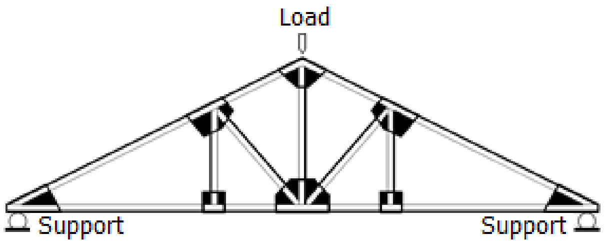

Fig. 6 Ideal truss model

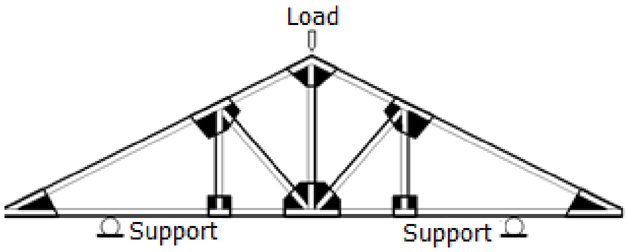

Fig. 7 As built truss model

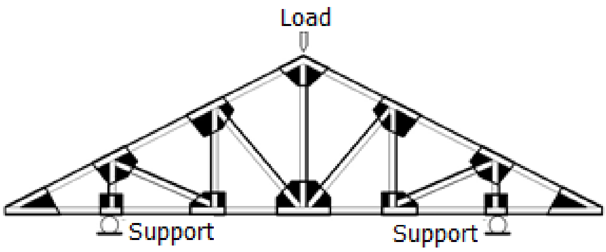

Fig. 8 Rectified truss model

The most appropriate remedial measure includes addition of a vertical member and an inclined web member forming a joint at the otherwise inappropriate support locations as shown Fig. 8. In order to quantify the contribution of this remedial measure towards recovering the loss in both strength and stiffness, another as built truss model was fabricated and then strengthened with the aforementioned remedial measure. This model is named as rectified truss model and will be required for detailed testing to assess the level of restoration. For future references this model is referred to as RTM (Rectified Truss Model)

The enhancement in load carrying capacity of the rectified truss model due to the remedial measure should be rationalized so as to quantify the percentage recovery achieved. This will help in evaluating the effectiveness of the proposed remedial measure.

3. Model analysis of scaled models

In professional structural design practice situations arise sometimes 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 2000). Since in the present project, the purpose of scale model testing was to validate the effectiveness of the proposed remedial measure. In addition, 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 steel truss models.

4. Experimental investigation

4.1 Model preparation

The truss was analyzed by the *method of joints* for an arbitrary load of 25 kN at the apex point which resulted in obtaining the maximum tensile force as 25 kN and compressive force as 27.96 kN. Accordingly, the truss of the model was designed complying with the Indian Standards [I.S. 800:2007]. The bottom chord, struts and the diagonal members were made up of single angle section ISA 25×25×5 [SP6(1): 1964] while the top chord was made up of double angle section ISA 25×25×5 (from buckling consideration) connected back to back. A 5mm thick gusset plate with 5 mm size fillet weld was used for connecting the members at joints (Subramanian 2010). The various geometrical dimensions of the truss model along with member details are given in Fig 9. The predicted design strength of this truss was 42 kN. Each model comprised of two trusses connected horizontally between corresponding

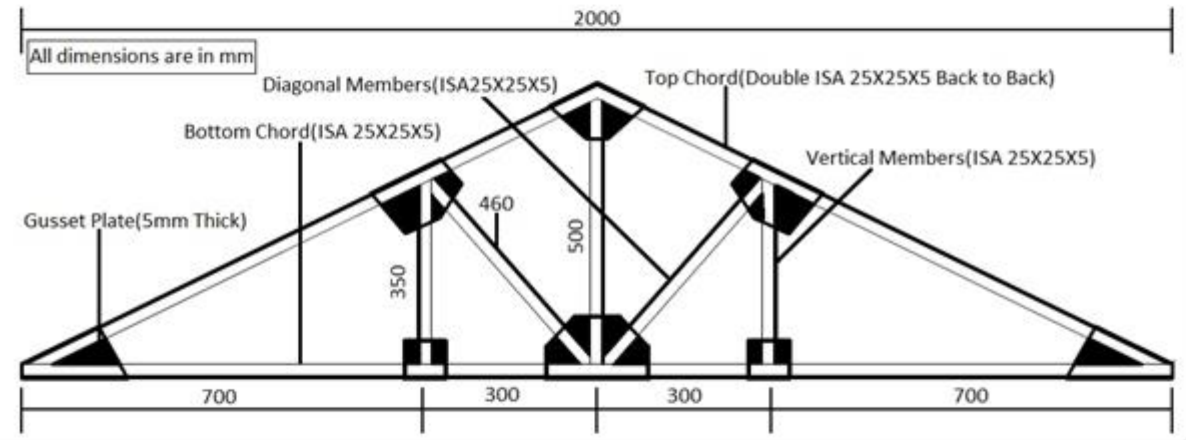

Fig. 9 Dimension details of the truss model

nodes by single angle section ISA 25×25×5 to avoid lateral instability and buckling.

4.2 Material properties

Tensile coupon tests were used to determine the mechanical properties of steel used. Three coupons were prepared from the center of the angle leg in the longitudinal direction. Various standards exist which specify the requirements for testing of tensile specimens. However the dimensions of the coupons, as conforming to the Indian Standards [I.S.1608:2005] is shown in Fig. 10. Computerized universal testing machine was used for conducting the tensile tests of the coupons as shown in the Fig. 11. The typical stress strain curve based on testing of coupon A is shown in the Fig. 12. The pattern of yielding of the test coupons can be seen in Fig. 13. The relevant material properties of the steel obtained from the material testing are given in Table 1.

4.3 Experimental setup

The model testing was carried out on a reaction frame of 500 kN capacity, 4 m long, 1.8 m wide and 2 m high. The load was applied by means of a hydraulic jack of 200 kN capacity which was transferred to the model through a proving ring of 200 kN capacity. Displacements produced under corresponding loads were recorded by digital dial gauges of least count 0.01 mm mounted at appropriate locations (Fig. 14). Since load applied through the hydraulic jack will act at single point only, necessary arrangements were made for the transfer of this point load to the apexes of the two trusses in the model. Stiff channel section ISMC 250(11mm thick) was used for the same. To ensure equal load distribution between the trusses in the model, a dial gauge was also mounted under the rigid transfer channel section to look for the variation in the deflection values with that of the central node of the bottom chord of the truss.

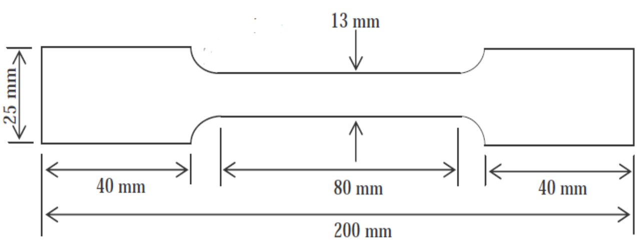

Fig. 10 Nominal dimensions of the tensile test specimen

Fig. 11 Tensile test coupon in the U.T.M.

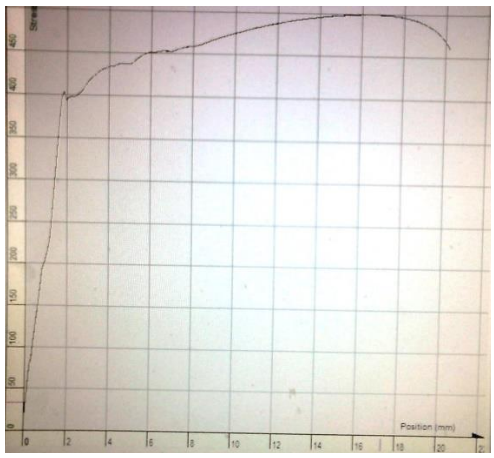

Fig. 12 Stress versus Strain curve of the tensile test

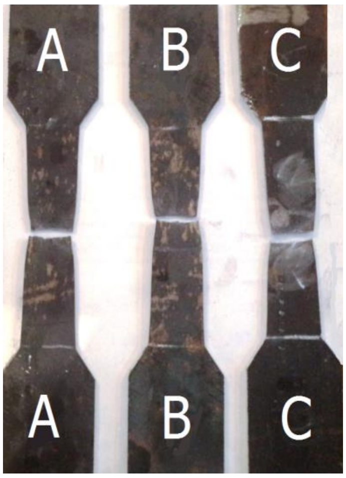

Fig. 13 Test specimens after tensile test

Table 1 Material properties of steel obtained from testing

Coupon	Nominal Strength	Modulus of Elasticity	Yield Strength	Ultimate Strength	Percentage elongation
	f_n (MPa)	E (GPa)	f_y (MPa)	f_u (MPa)	(%)
A	250	214.2	264.7	432.8	24
B	250	212.9	271.3	455.4	23
C	250	214.4	278.6	443.2	24

Before carrying out the serious experimental work for achieving well defined objectives from high precision experimental testing, it is essential to critically evaluate the performance of the experimental set-up being used for this 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 course of action is to perform preliminary testing on a trial model as shown in Fig. 15. This will not only help in checking the performance of loading frame but also help in identifying the shortcomings (if any) in the trial model, and also provide clues to make necessary changes in the truss models for obtaining better results (Dar *et al.* 2015). A trial model was set-up and loaded up to 10 kN for testing the performance of the loading frame and hydraulic jack.

Since no shortcomings were found in the trial testing all the three models were mounted for testing one after the other. Deflections at corresponding loads were recorded for all the models.

5. Test results & discussion

The experimental data recorded during testing for all the three truss models needed to be analyzed to facilitate a meaningful interpretation. Graphical representation of load versus deflection data is very helpful to get a physical feel about the structural response to applied loading. Figure:16 shows load versus deflection curve of ITM at central node and other node. Fig. 17 and Fig. 18 shows the load versus deflection curve of BTM and RTM at central node respectively. For the sake of comparison, the load versus deflection curve of all the models at central node is shown on a single plot(See Fig. 19).

5.1 Result interpretation & discussion

Fig. 16 shows that in ITM the load deflection behavior is nearly linear till 62 kN with a deflection of 0.92 mm at center and 0.8 mm at the left node. Beyond this point, stiffness drops. This model finally fails at a load of 87.24 kN with a deflection of 2.45 mm at center and
2.17 mm at the left node.

Fig. 17 shows that in BTM the load deflection behavior in nearly linear till 33 kN with a central deflection of 8.1 mm. Beyond this point, stiffness drops until 70 kN with a central deflection of 40.16 mm. The stiffness further drops and the model finally failed at a load of 72.26 kN with a central deflection of 48.63 mm.

Fig. 18 shows that in RTM the load deflection behavior in nearly linear till 150 kN with a central deflection of 2.85 mm. Beyond this point, stiffness drops and finally this model fails at a load of 157.72 kN with a central deflection of 3.39 mm.

Fig. 19 shows a comparison of load versus central deflection curve of all the truss models.

The load carried by ITM is 1.2 times than that of BTM. After implementing the remedial measure, RTM is able to carry 2.2 times the load of BTM. As mentioned earlier, the improper location of the supports made the distressed truss to exhibit more flexural behavior than a truss behavior. With the result, the main cause of excessive deflection in BTM is mainly due to localized flexural deformation of improperly supported end panels of the bottom chord rather than axial deformation of the various truss members. However the behavior of the same was expressed in terms of stiffness of the truss (load required per unit central deflection) for appropriate interpretation. Loss in stiffness in BTM=95.7%. Increase in stiffness achieved through remedial measure in RTM=126.35%. Reduction in load carrying capacity in BTM=17.17%. Increase in load carrying capacity achieved through remedial measure in RTM=97.94%.

From the above it is concluded that, by just introducing a joint (which utilizes only 5% of extra steel) at the appropriate location (i.e., at the support) in the ‘as built truss’, stiffness in general and load carrying capacity in particular improved drastically which is favorable from safety consideration. The results indicate that the remedial measure enhanced the load carrying capacity and stiffness by nearly 6 times and 1.5 times respectively, thus validating

Table 2 Load carrying capacity trend in kN

Particulars of the Model	Nominal load (kN)	Failure load (kN)	Max. deflection measured at locations (mm)				Stiffness (kN/mm)
			center		left		
			A	B	A	B	
RTM	84	157.7	3.39	2.14	3.13	1.80	46.52
ITM	84	87.24	2.45	1.32	2.17	1.21	35.61
BTM	--	72.26	48.63	42.99	44.26	41.75	1.53

A: Experimental results, B: Analytical results

Fig. 14 Experimental Set-up details & dial gauge locations

Fig. 15 Preliminary testing on a trial model

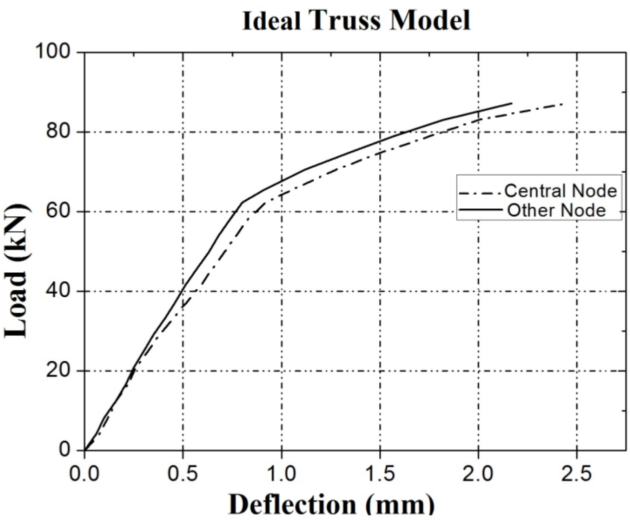

Fig. 16 Load versus deflection curve of ITM

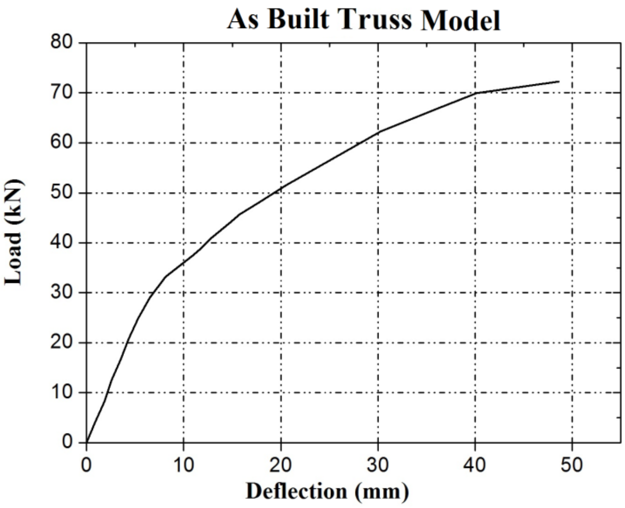

Fig. 17 Load versus deflection curve of BTM

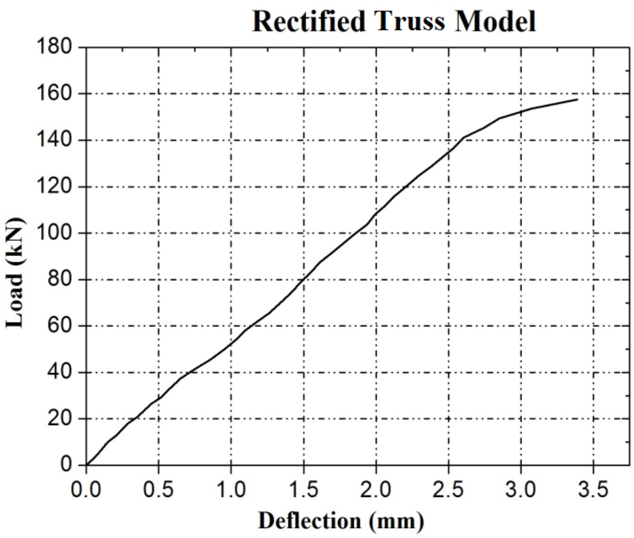

Fig. 18 Load versus deflection curve of RTM

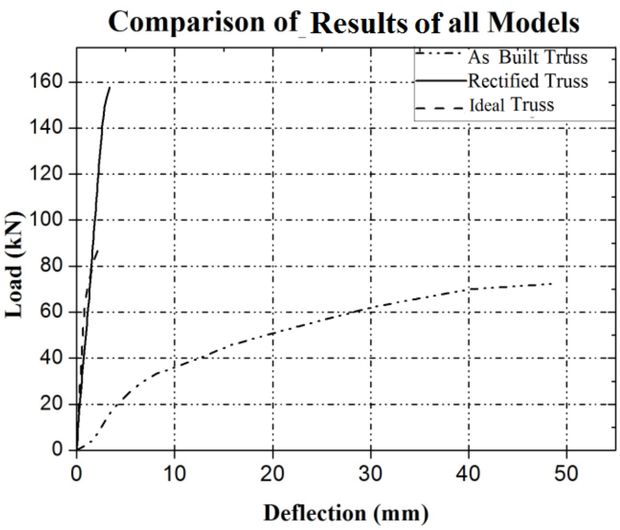

Fig. 19 Load versus deflection curve of all the models

Fig. 20 Failure mode - experimental versus analytical model

the effectiveness of the proposed remedial measure. The judiciously proposed remedial measure, isable to rectify the behavior of distressed roof truss, particularly strength-wise, beyond the desired level.

6. Analytical study

To verify the accuracy of the experimental results, an analytical study was carried out at failure loads in all the models using STAAD Pro V8i. The results of this analytical study were later compared with that of the experimental ones as given in Table 2. Fig. 20 presents the characteristic failure mode for experimentally tested and analytically simulated as built truss model. In all three models an acceptable variation between the experimental and analytical results was observed. This variation was mainly due to geometrical imperfections, material non-linearity and

Table 3 Summary of parametric study-I results

Section used	Area of cross section (mm^2)	Max. deflection measured at locations (mm)			Stiffness (kN/mm)
		Center	Left	Horizontal	
ISA 20×20×3	112	1.086	0.855	0	92.08
ISA 20×20×4	145	0.930	0.700	0	107.52
ISA 25×25×3	141	0.945	0.714	0	105.82
ISA 25×25×4	184	0.817	0.586	0	122.39
ISA 25×25×5	225	0.740	0.510	0	135.13
ISA 30×20×3	141	0.945	0.715	0	105.82
ISA 30×20×4	184	0.817	0.587	0	122.39
ISA 30×20×5	225	0.740	0.510	0	135.13
ISA 30×30×3	173	0.843	0.612	0	118.62
ISA 30×30×4	226	0.738	0.508	0	135.50
ISA 30×30×5	277	0.675	0.444	0	148.14
ISA 35×35×3	203	0.776	0.548	0	128.86
ISA 35×35×4	266	0.686	0.455	0	145.77
ISA 35×35×5	327	0.631	0.401	0	158.47
ISA 40×20×3	162	0.844	0.614	0	118.48
ISA 40×20×4	208	0.739	0.508	0	135.31
ISA 40×20×5	251	0.675	0.445	0	148.14
ISA 40×25×3	188	0.808	0.577	0	123.76
ISA 40×25×4	246	0.710	0.480	0	140.84
ISA 40×25×5	302	0.651	0.421	0	153.60
ISA 40×25×6	416	0.612	0.382	0	163.39

Table 4 Summary of parametric study-II results

Section used	Area of cross section (mm^2)	Max. deflection measured at locations (mm)			Stiffness (kN/mm)
		Center	Left	Horizontal	
ISA 20×20×4	145	1.042	0.812	0	95.96
ISA 25×25×3	141	1.045	0.815	0	95.69
ISA 25×25×4	184	1.010	0.779	0	99.00
ISA 25×25×5	225	0.962	0.732	0	103.95
ISA 30×20×3	141	1.046	0.816	0	95.60
ISA 30×20×4	184	1.010	0.780	0	99.00
ISA 30×20×5	225	0.989	0.759	0	101.11
ISA 30×30×3	173	1.016	0.785	0	98.42
ISA 30×30×4	226	0.986	0.756	0	101.41
ISA 30×30×5	277	0.968	0.738	0	103.30
ISA 35×35×3	203	0.996	0.766	0	100.40
ISA 35×35×4	266	0.970	0.740	0	103.09
ISA 35×35×5	327	0.954	0.724	0	104.82
ISA 40×20×3	162	1.018	0.787	0	98.23
ISA 40×20×4	208	0.998	0.758	0	100.20
ISA 40×20×5	251	0.971	0.740	0	102.98
ISA 40×25×3	188	1.006	0.776	0	99.40
ISA 40×25×4	246	0.979	0.749	0	102.14
ISA 40×25×5	302	0.962	0.732	0	103.95
ISA 40×25×6	416	0.951	0.721	0	105.15

experimental errors if any.

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:

RTM > ITM > BTM

7. Parametric study

There was a reasonable agreement between the experimental and analytical results. Therefore a parametric study (parametric study-I) was carried out using the same analytical model to examine the influence on strength and stiffness due to different angle cross sections used as vertical and inclined web members of the truss to support an apex load of 100 kN. A total of 41 models were included in the parametric study. Different angle sections ranging from ISA 20×20×3 to ISA 40×25×6 from Special Publications of Indian Standards (SP6(1):1964) were used. Table 3 summarizes the results of parametric study-I.

In another parametric study (parametric study-II), only the vertical member at the truss support experiencing compressive stresses was changed while the inclined web member experiencing tensile stresses was kept the same (i.e., ISA 20×20×3). The main reason for keeping this tension member of the truss the least was that tension members experience more or less uniform stresses and do not undergo buckling (Shiyekar 2015). The effect of this variation on the strength & stiffness of the truss under the same apex load of 100 kN was also investigated. The summary of this parametric study in given in Table 4.

8. Conclusions

The structure studied in this paper was in a complex situation, as it was neither economical nor feasible to remove the distressed trusses and fabricate new ones. Rehabilitating the distressed trusses in order to satisfy the strength and serviceability requirement without sizable financial loss was the most appropriate solution to this complicated problem. The distressed truss had mainly suffered a drastic stiffness loss of 95.7% accompanied by a strength loss of 17.17%. The experimental study indicated that by just using 5% extra material (additional members at support), the stiffness of this distressed truss increased by 126.35% and load carrying capacity by 97.94%. It is worth mentioning that experimental and analytical results were in reasonable agreement, hence validating the experimental results. The parametric study indicated that as the cross sectional area of both the vertical and inclined web member at the truss support increases individually and collectively, the strength and stiffness increases. In addition, proper analysis and assessment of the problem, as well as the proposed reliable solution lead to promising results. The successful experimentation has greatly contributed in making the roof truss structurally safe, hence fulfilling the main objective of structural design.

Acknowledgements

The authors sincerely thank CONSULTING ENGINEERS, PVT. LTD. for providing all the necessary details required for studying this problem. The authors also thank M.S.R.I.T. Alumni Association, Bangalore for their funding used for procurement of the steel.

References

Abramyana, S.G. and Ishmametova, R.K. (2016), "Strengthening timber roof trusses during building construction and reconstruction", *International Conference on Industrial Engineering*, ICIE 2016, Procedia Engineering, doi: 10.1016/j.proeng.2016.07.253.

Anbarasu, M. (2016), "Local-distortional buckling interaction on cold formed steel lipped channel beams", *Thin Wall. Struct.*, **98**, 351-359.

Barbari, M., Cavalli, A., Fiorineschi, L., Monti, M. and Togni, M. (2014), "Innovative connection in wooden trusses", *Constr. Build. Mater*., **66**, 654-663.

Branco, J.M., Piazza, M. and Cruz, P.J.S. (2010), "Structural analysis of two King-post timber trusses: Non-destructive evaluation and load-carrying tests", *Constr. Build. Mater.*, **24**(3), 371-383.

Burdzik, W.M.G. and Skorpen, S.A. (2014), "Metal-strip bracing versus diagonal timber bracing in timber trussed tiled roofs", *Eng. Struct*., **75**, 1-10.

Dar, M.A., Subramanian, N., Dar, A.R. and Raju, J. (2015), "Experimental investigations on the structural behaviour of a distressed bridge", *Struct. Eng. Mech*., **56**(4), 695-705.

Dawe, J.L., Liu, Y. and Li, J.Y. (2010), "Strength and behaviour of cold-formed steel offset trusses", *J. Constr. Steel Res*., **66**(4), 556-565.

Foo, H.C. (1993), "Experimental study on timber trusses and joints", *J. Struct. Eng*., **119**(4), 1283-1296.

Ganesan, T.P. (2000), *Model Analysis of Structures*, University Press, Hyderabad.

Hibbler, R.C. (2008), *Structural Analysis*, 6th Edition, Pearson Education, (pp. 79-111). Upper Saddle River, New Jersey.

I.S.1608 (2005), Indian Standard- Metallic Materials - Tensile Testing at Ambient Temperature, Bureau of Indian Standards, New Delhi, India.

I.S.800 (2007), Indian Standard- General Construction in Steel, Code of Practice, Bureau of Indian Standards, New Delhi, India.

Jagadish, R. (1995), Structural Failures, Case Histories, Oxford & IBH Publishing, Delhi.

Munafò, P., Stazi, F., Tassi, C. and Davi, F. (2015), "Experimentation on historic timber trusses to identify repair techniques compliant with the original structural-constructive conception", *Constr. Build. Mater*., **87**, 54-66.

Piroglu, F. and Ozakgul, K. (2016), "Partial collapses experienced for a steel space truss roof structure induced by ice ponds", *Eng. Fail. Anal*., **60**, 155-165.

Piroglu, F., Ozakgul, K., Iskender, H., Trabzon, L. and Kahya, C. (2014), "Site Investigations of damages occurred in a steel space truss roof structure due to ponding", *Eng. Fail. Anal*., **36**, 301-313.

Schodek, D.L. (2000), *Structures*, 4th Edition (pp.15, and pp.132-57). Prentice Hall, Upper Saddle River, New Jersey.

Shiyekar, M.R. (2015), *Limit State Design in Structural Steel*, 2nd Edition, Prentice Hall India, New Delhi.

SP 6(1) (1964), Handbook for Structural Engineers, Structural Steel Sections. Bureau of Indian Standards, New Delhi, India.

Subramanian, N. (1998), "Rehabilitation of steel structures- some case studies", *Advanced Course on Design of Steel Skeletal Structures*, SERC, Madras.

Subramanian, N. (2010), Steel Structures, Design and Practice (pp. 113-31, 193-227, 266-97, and pp.570-72), Oxford University Press, New Delhi.

Subramanian, N. (2014), "Codification and methods to improve the Process", *Bridge Struct. Engineer*, **44**(2), 1-12.

Subramanian, N. (2014), "The failures that changed the perception of our designs", *Bridge Struct. Engineer*, **45**(4), 24-44.

STAAD.ProV8i, Technical Reference Manual, Bentley Systems; 2012.

CC