COMPARATIVE STUDY ON STRENGTHENING METHODS OF STEEL TOWERS

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Abstract: Steel towers are widely used in the telecommunication and power transmission sectors. Failure of these towers causes direct and indirect losses and disruption to the services provided by those towers. As a result, industries and general public face difficulties and the productivity of the country also gets affected. Considerable number of tower failures has taken place in both power transmission and telecommunication sectors of Sri Lanka in the recent past but only a little amount of studies has been done so far. Testing at least a tower in a transmission line is mandatory in the power transmission sector of Sri Lanka. Generally these tests are carried out at the Structural Engineering Research Centre in Chennai. It has been observed that several towers fail prematurely under normal loading conditions during full scale tests, indicating lack of strength of towers. The objectives of this study are analysing tested towers using finite element method and comparatively studying different techniques of strengthening of towers. A general purpose finite element analysis program SAP2000 was used for the modelling and analysis of towers. Finite element model of a tower which has been tested to full scale was developed and validated in SAP2000. Then different methods of strengthening were carried out to the validated model to comparatively study the effect of each method on the strength of the tower. The findings are presented in this paper.

Keywords: Steel Towers, Finite Element Analysis, Strengthening Methods

1. Introduction

Steel towers are very widely used in the telecommunication and power transmission sectors. These towers are not just vital components of the utilities but also of the economy, productivity and growth of a country and the well-being of the people in that country.

Lattice towers are the most common type of towers found in both telecommunication and power transmission sectors of Sri Lanka. These are generally made up of steel angle and tubular sections. These structures can be categorized as space trusses or space frames based on the rigidity of the connections. Usually lattice towers are analysed as space trusses whose members are either in tension or compression and do not carry moments or shear forces. In the actual case neither fully rigid nor fully pinned condition exists.

Many tower failures take place around the world, but most of them do not catch the attention of media as they usually occur in remote areas with low populations and cause very few or no loss of life. Failure of a telecommunication or transmission tower could not just lead to the direct losses but also to indirect costs due to disruption of the service provided by the tower and the costs associated with litigation. This can also hinder the productivity of the country by causing delays and interruption to the normal day to day activities.

Telecommunication sector of Sri Lanka recommends wind tunnel tests to ensure the design of towers. According to Baskaran et.al 2011, although many telecommunication tower failures have been observed in the recent past, no technical reports on failures are available. Only non-technical reports are prepared for the purpose of claiming insurance and literally nothing has been learnt from those failures. Therefore, the reasons for the failures cannot

be identified and the necessary remedial actions that need to be adopted cannot be thought of.
Testing at least a tower in a transmission line is mandatory in the power transmission sector of Sri Lanka. Generally these tests are carried out at the Structural Engineering Research Centre in Chennai. Many premature failures have been observed during full scale tests as per Rao et.al 2010. These failures result in delays and cause additional expenses to the client. Premature failure of towers is a clear indication of lack of strength of towers. Therefore, there is a need to assess the strength of the towers and adopt suitable methods of strengthening to the existing towers which lack strength; and revise the methods of design of the future towers.

Albermani et.al 2009, da Silva et.al 2005and Baskaran et.al 2011 have presented methods of strength assessment and failure prediction of steel towers based on their studies.Albermani et.al 2004 presented efficient upgrade schemes using diaphragm bracings.The improvement of tower strength with addition of different diaphragm bracings at different heights of the slender diagonal members was studied by considering a tower substructure.The study showed that significant strength improvements could be achieved using diaphragm bracings at mid heights.Mills et.al 2012 studied multi-panel retrofitted transmission towers experimentally. The study focused on retrofitting the main leg members of steel lattice transmission towers by steel angles through bolted double steel angle connectors.The overall efficiencies of the method ranged between 54% to 105% increase in tower capacity.

Xie and Sun 2012proposed that sufficient diaphragms should be added in each panel of the lattice transmission towers considering the load carrying capacity and deformability simultaneously.Zhuge et.al 2012 investigated the most efficient leg retrofitting system through an experimental program using one panel angle leg retrofitting model and a nonlinear finite element model. Three different arrangements of interconnectors namely, aligned type, alternate type and cruciform type were studied and it was concluded that the cruciform type provided the highest average strength increase. The study also identified that the leg reinforcing method is effective in increasing the load carrying capacity. Jesumi et.al 2013 proposed the optimal bracing system for steel towers considering a balance between economy and stability against lateral forces.

Although significant amount of studies have been done in this area in other countries not much has been done in Sri Lanka. Therefore, there is a need to fill the gap existing in this field of study and this study focuses on moving a step forward in doing so.

2. Analytical Study

The objective of this study is to develop a simple method to assess the strength of towers which will provide the information required for the determination of the need of strengthening of towers and to assess the contribution of each strengthening method to the strength of the tower and to use it to comparatively study different strengthening methods of towers.

A finite element model of a tested transmission tower was developed for the study to assess the strength and comparatively study different strengthening methods. The model was developed using SAP2000, a general purpose finite element software package.

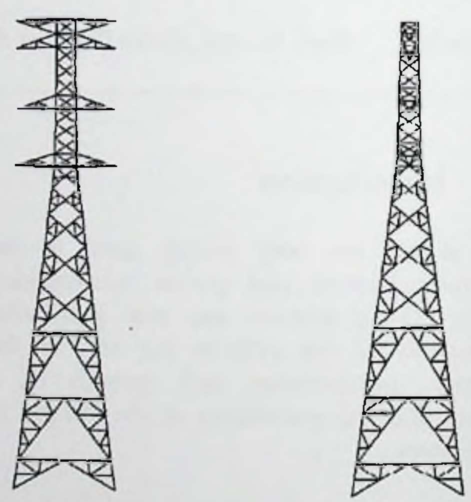

Figure 1: Arrangement of the tested 132 kV double circuit "TDL" type tower.

The tower which was used for the study is a 132 kV double circuit "TDL" type tower of 39.56 m height and 9.489 m base width with +12 m body extension as shown in Figure 1. Thiswas tested as per the international standard IEC 60 652 2002-06 and the testing was done at the Structural Engineering Research Centre (SERC) in Chennai. The test programme covered eight different loading cases. The tower successfully withstood all eight load cases and a destruction test was carried out thereafter. The tower was loaded up to 120 % and at this load, two main leg members highlighted in Figure 2 failed by buckling.

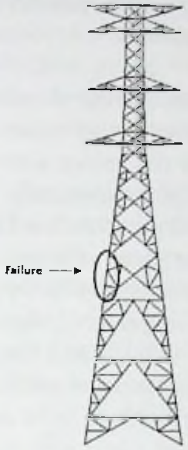

Figure 2: Failure location during the destruction test.

3. Finite Element Modelling

The tower was modelled using 887 frame elements includingall redundant members, vertical bracing members, arm members and diaphragm members and 553 joints, as a three dimensional space frame with legs, some of the vertical and horizontal bracings and arm members being continuous as in the actual tower. The supports of the tower were modelled as pinned.

Steel angle sections 45x45x5, 50x50x5, 55x55x5, 60x60x5, 65x65x5,65x65x6, 70x70x6,75x75x6, 100x100x6, 100x100x7, 100x100x8 and 110x110x8 of steel grades S275JR and S355JR of BS EN 10025 : Part 2 : 2004 were usedin the development of the model.

Modelling of the tower was very straightforward even though the geometric arrangement was a little complicated since the tower is fully made up of straight frame elements connected to nodes. Special attention was paid when modelling the vertical cross bracings of all four faces of the tower because these members were connected to each other at the crossing point.

The tower was analysed under linear static case and the design check utility of SAP2000 was used to check the members individually and observe whether they were overstressed or not. Although non-linear analysis is the most appropriate one for this kind of study, linear elastic analysis was carried out to study how accurate the traditional linear elastic method can be in predicting failures. Since not much literature is available in Sri Lanka on modelling of steel transmission towers and failure analysis, it was decided to go ahead with linear elastic analysis as a first step in filling the gap in this area of study. Figure 3 shows the complete model of the transmission tower developed using SAP2000. All eight load cases and the destruction load case were defined and assigned to the model as per the specifications for each of the loading cases.

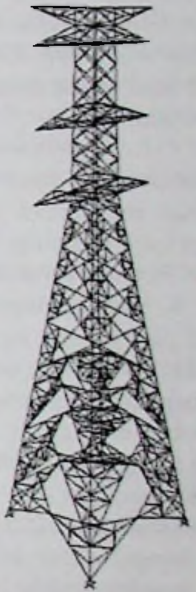

Figure 3: SAP2000 model of the tower

4. Verifications

The model was analysed under all the loading cases and the design check utility of SAP2000 using the American Standard ASCE10-97 was used to check the stress conditions of each member. In order to ensure that the design check utility is correct; manual capacity check for all the members were carried out independently using ASCE 10-97 and compared with SAP2000 design check outputs. From the analysis it was found that 89 % of members were in good agreement showing less than or equal to 10 % deviation. Only 6 % of the members showed capacities deviating more than 20% from those calculated manually.

An important point to note here is that most of the deviating members were found to be horizontal diaphragm bracings and the American code does not provide clear guidelines to design horizontal bracings and arm members. Therefore the difference between manual calculations and the SAP2000 design check calculations could be due to this reason. Since about 90 % of the members were in good agreement with the manual calculations the design check utility was used for thesubsequent analyses.

The design check outputs of SAP2000 are given in the form of PMM ratios which takes into account both axial and bending effects of the members. Although the structure is assumed to be a truss carrying primarily axial forces, significant bending effects were also identified in some members. Therefore, the PMM ratios were used as the means to predict failures in the analysis.

The results of the analysis from all the load cases showed that the model was able to predict the failure approximately. The analysis showed that two bottom most leg members and four of the K bracings members of the second and third panels were overstressed. It was also found that no failures were exhibited till 120 % of the load which means that the model was capable enough to predict the failure load even though the location differed. In fact the PMM ratios of the overstressed members obtained from SAP2000 design check were very close to each other which indicate that any of these members might havefailed.

The model was considered acceptable because the model was developed with pinned connections and only a linear elastic analysis was carried out. The load path could have differed from that of the actual case due to any of these reasons but yet the model was able to predict the failure load and the failure mode. Therefore, the model was consideredas a valid one and the strengthening techniques were applied to this validated model with the focus of eliminating the identified failures.

5. Strengthening Methods

During the search of strengthening methods of steel towers from both literature survey and discussions with personnel in the industry, different methods of strengthening methods were identified. These methods can be broadly categorized into three: Provision of horizontal bracing diaphragms, Upgrading of tower leg members and Replacement of members. This paper covers the studies that were carried out with the last two methods only as complete details on the implementation of first method to actual towers were not available.

The strengthening methods identified were applied to the validated tower model in order to eliminate the weaknesses of the tower and strengthen it. The weight increase resulting from each strengthening technique was used as a parameter to identify the most efficient strengthening method as the weight is directly related to the cost of strengthening.Initially the total weight of the tower was 74.78 kN and the weight and behaviour of the tower after each trial were recorded as shown in Table 1.

Table 1: Trials and Observations

<table>
<tr><th colspan="2">Trial</th><th>Tower weight (kN)</th><th>Observations</th></tr>
<tr><td rowspan="3">Replacement of Bracings</td><td>1</td><td>75.22</td><td>Two legs and a bracing remained overstressed.</td></tr>
<tr><td>2</td><td>75.67</td><td>Two legs and a bracing remained overstressed.</td></tr>
<tr><td>3</td><td>77.84</td><td>Tower became safe</td></tr>
<tr><td rowspan="3">Leg upgrade using cruciform type arrangement</td><td>1</td><td>76.37</td><td>The overstressed legs became safe but legs in the next panel were overstressed</td></tr>
<tr><td>2</td><td>79.56</td><td>The overstressed legs became safe but legs in the next panel were overstressed</td></tr>
<tr><td>3</td><td>82.74</td><td>The legs became safe</td></tr>
<tr><td rowspan="3">Leg upgrade using back to back type arrangement</td><td>1</td><td>76.30</td><td>The overstressed legs became safe but legs in the next panel were overstressed</td></tr>
<tr><td>2</td><td>79.34</td><td>The overstressed legs became safe but legs in the next panel were overstressed</td></tr>
<tr><td>3</td><td>82.38</td><td>The legs became safe</td></tr>
</table>

5.1 Replacement of Bracing Members

Replacement of bracing members was carried out in steps with the focus of eliminating the failure.In the first trial all four bracings which were found to be failing were replaced with 60x60x5(S275JR) sections and the model was analysed. The total weight of the tower after strengthening was 75.22 kN (0.6 % weight increase). But a vertical k bracing was foundto be failing and was more critical than the other members. The other vertical k bracing members became marginally safe.Small reduction in the PMM values of leg members was observed but the two leg members remained overstressed.

In the second trial all four bracings were replaced with 65x65x5(S275JR) sections and the model was analysed. The total weight of the tower after strengthening was 75.67 kN (1.2 % weight increase).The leg members became more critical (but failing marginally) and in fact those were the only two members to fail. But only a marginal difference between legs and bracings was observed and all four bracingmembers became safe.Small reduction in the PMM values of leg members was also observed.

In the third trial all four bracings were replaced with 70x70x6 (S275JR)sections and the model was analysed. The total weight of the tower after strengthening was 77.84 kN (4.1 % weight increase).All the members appeared to be safe but the PMMs of main leg members were very close to the limiting value. Small reduction in the PMM values of leg members was also observed.

5.2 Upgrade of Leg Members Using Cruciform Type Leg Member Upgrade

The problem with using these members is that most of the available design codes including ASCE 10-97 do not provide any guidelines for the design of these members. Therefore the design check utility of SAP2000 using ASCE 10-97 could not be used for the analysis. But it was identified that the effect of strengthening of legs would not be able prevent a failure in the bracings. Therefore the objective of the experiment was refined to elimination of leg member failure by leg upgrade.

As a solution to the problem of non availability of design guidelines in ASCE 10-97 for the analysis of retrofitted leg members, the Indian code IS 800:1998 - General Construction in Steel was used.In order to ensure that the design check using IS 800:1998 can be used, the original tower was analysed using this code and compared with the design check using ASCE 10-97. The same two legs were found to be failing at the same locations as in the analysis using ASCE 10-97. In addition the members of same legs in the panel immediately above were also found to be failing. Therefore it was confirmed that the two design checks are in good agreement for the leg members and the study was continued using the Indian code for the analysis.

In the first trial another 110x110x8 (S355JR) member was connected to each of the bottommost legs in a cruciform shape and analysed.The overall weight of the structure was found to be 76.37 kN (2.1%weight increase). The analysis showed that the two bottom legs became safe with low stress levels after the application of the strengthening technique. But the second panel legs for which strengthening were not carried out were found to be failing although these members did not fail in the original analysis. Therefore upgrade had to be done to the second bottommost panel as well.

Table 2 : Summary of the results of strengthening experiments

Type of strengthening	% weight increase to eliminate failure	Type / Mode of failure eliminated
Replacement of Bracings	4.1	All
Leg upgrade using cruciform type arrangement	10.6	Leg member failure
Leg upgrade using back to back type arrangement	10.2	Leg member failure

In the second trial, 110x110x8(S355JR) members were connected to the two bottommost panel legs in a cruciform shape and analysed.The overall weight of the structure was found to be 79.56 kN (6.4% weight increase). The analysis showed that the legs became safe with very low stress levels after the application of the strengthening technique. But the third panel legs for which strengthening was not carried out was found to be stressed little more than it was. Even though it was within the safe limits it was very marginal. This effect was found in the panels above as well but they were not as critical as the third panel.Therefore, the upgrade was done to the third panel as well.

In the third trial the upgrade was done to the third panel as well. With this, the stress levels in all the leg members including the ones in the next top panel reduced. The structure became safe against leg failure.The overall weight of the structure was found to be 82.74 kN(10.6 % weight increase).

5.3 Upgrade of Leg Members Using Back to Back Type Leg Member Upgrade

Using this arrangement for upgrade was found to exhibit very similar behaviour to those observed when the cruciform type upgrade was used. The same three trials with same sections were tried with a back to back arrangement and the observations were very similar to those observed when the cruciform type was used although the PMM values slightly differed.Table 2 provides the summary of the results obtained from all the experiments.

6. Conclusions

Linear finite element models can be used to approximately assess the strength of steel towers and to predict failures. The analysis showed that the bending effects in the continuous memberscan be as high as or even higher than the axial force effects. Therefore, the bending effects should not be neglected even though the traditional design practice assumes the tower as a three dimensional truss carrying only axial forces.The following conclusions were drawn from the results obtained from the finite element analysis using the strengthening methods.

- Strengthening of bracing members can reduce not just the stress levels of bracing members but also the stress levels of main leg members. The reduction in the stress levels of main leg members is significant such that it can be used to eliminate the both the failure modes.
- Upgrading of leg members can only be used to strengthen the leg members of the tower. This technique will not have much effect in reducing the stress levels of the bracing members.
- Upgrading of leg members using both cruciform type arrangement and back to back type arrangement has almost the same effect on the strength of the tower.
- When upgrading the leg members, in both types, the connecting member should at least extend to the adjacent panel to obtain sufficient strength increase otherwise the leg members in the adjacent panel may be overstressed as a result of strengthening.
- When upgrading the leg members it is preferable to extend the strengthening section to the two adjacent panels to have the optimum effect.
- Strengthening of leg members is expensive as it requires more steel and special construction techniques to properly support and transmit the load to the footings.

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