STRENGTH ASSESSMENT OF STEEL TOWERS

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Abstract: In the recent past, considerable number of tower failures happened in telecommunication sector and power transmission sector in Sri Lanka. However, no lessons were learnt and there is still a vacuum in strength assessment of towers. The objectives of this research are conducting data survey on failed towers in Sri Lanka and identifying causes, analysing failed electric transmission towers using finite element analysis and finding the causes for the failures and developing simple methods to check tower capacity based on available simplified models. Four telecommunication towers and a transmission tower were considered to identify the failure reasons. Structural analysis of a transmission tower was done using a finite element analysis package, SAP2000. A manual method to analyse 3D trusses was developed by combining unit load method and tension coefficient method. To ensure the validity of proposed analysis methods, a simple tower model was erected, structural analysis was done using both SAP 2000 package and manual method, failure loads were predicted using SAP 2000 package, loading was conducted and results were analysed. It is concluded that preliminary structural analysis with a specialised or a common structural analysis package, has to be incorporated into prevailing steel tower design procedures. Frequently admitted reason for telecommunication tower failures is tornados. However, nowadays towers are being overloaded with antennas without proper consultation. Therefore it is essential to carry out a detailed technical failure analysis to identify the reasons of failures. All these procedures and results obtained are discussed in detail in this paper.

Keywords: Steel Tower Failures, Structural Analysis, Tension Coefficient Method

1. Introduction

Steel towers are being widely used in telecommunication and power transmission sectors of Sri Lanka. Several tower failures occurred in recent past. But failures were not analysed to find out the causes and no lessons were learnt from the failures. Continuation of mistakes or drawbacks is obvious due to this trend prevailing in the industry.

In power transmission sector, testing at least a tower per transmission line is mandatory. This method is recommended because of the complicated nature of structural behaviour of lattice towers and the errors made during construction. Several towers are failing frequently during tests, even for the normal condition loads. These failures are causing delays and increased consultant charges.
Strength checks of telecommunication towers are verified by conducting wind tunnel test. But several tower failures have taken place in recent past.Whenever a tower fails the firm that owns the tower used to remove the debris as soon as possible, produce a report that is not technical and not available to public and claim insurance. Tower failures interfere with provision of services. Due of this, both public and industries are getting affected and ultimately resulting in reduction of country's productivity. The most important issue is that, structural design firms of Sri Lanka may lose their credibility because of frequent tower failures. So reasons must be found for past failures in order to overcome above mentioned problems.

Objectives of the current research are identifying the reasons for failure of towers and proposing methods to assess the tower strength capacities. No remarkable work has been carried out in Sri Lanka, regarding tower failures. But worldwide, several studies were done regarding tower failure. Different types of premature failures observed during full-scale testing of Transmission line towers at Tower Testing and Research Station, Structural Engineering Research Centre (SERC), Chennai were studied and the reasons for failures were discussed in detail in Prasad Raoet al (2009) and Prasad Raoet.al(2010).

A forensic analysis in order to investigate the failure causes for towers failed duringstrong south-west wind and heavy snowfall in the region Münsterland, north-western part of Germany was done and causes were found in Klingeret.al (2011). Several researches were done regarding non-linear analysis of towers, joint effects, bolt slippage, buckling mechanisms in members, different bracing arrangements and other aspects of steel lattice towers.

2. Review on reported collapse of steel towers

Four telecommunication tower failures and a transmission tower failure were analysed to find the failure causes. As all details were not available, causes were identified from relevant officials' comments and interpretations of photographs obtained. Summary of analysis is given in table 1.

The transmission tower failed while testing under normal condition- maximum vertical load (lc11) condition and normal condition-minimum vertical load (lc10) condition. Under lc 10 bottom panel leg member failed due to compression buckling. Failed members (100x100x8) were replaced with larger members (100x100x10) and then loaded for lc10. No failures occurred so loading proceeded to lc11. Under lc11 second panel leg member failed due to compression buckling. Reason for the failure is due to improper design of tower.

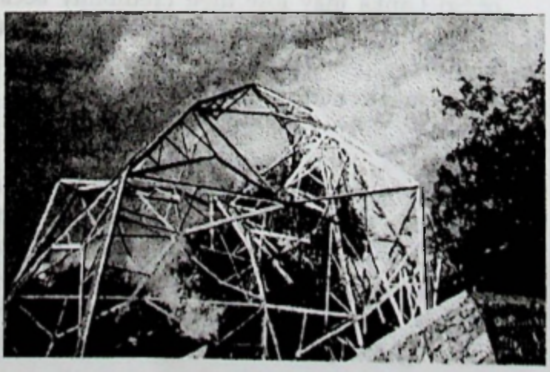

Fig 1 Beliaththa 70m antennatowercollapse

Fig 2 Mihinthale 70m antenna tower collapse

Fig 3Gampaha 70m antenna tower collapse

Fig 4Horowpathana 70m antenna tower collapse

3. Computer analysis of steel transmission tower

For computer analysis of steel transmission towers, SAP 2000 was used. Ceylon Electricity Board has made the testing of at least one tower per transmission line mandatory. Usually these tests are done by SERC, Chennai and a report is produced. A similar test report of a tower of Horana grid was obtained and used for analysis purposes. This tower is a vertical double circuit tower having a height of 40m and a width of 8.7m at bottom.

Table 1. Summary of analysis of tower collapses

Description of antenna tower	Design as	Possible reasons for failure	Failure pattern info:
70m high at Beliatta (Mobitel) *See Fig 1*	Four legged steel lattice structure, designed for 10sqm antenna area	Improper erection procedures adopted. Erected without providing any of inner plan bracings. The use of temporary guy ropes in unsymmetrical manner.	Collapsed at second panel
70m high at Mihintale (Sri Lanka Telecom) *See Fig 2*	Four legged steel lattice structure, designed for 10sqm antenna area.	Due to tornado situation	Collapsed at second panel Twisting of the structure in its own axis during the collapse
70m high at Gampaha (Mobitel) *See Fig 3*	Four legged steel lattice structure, designed for 10sqm antenna area.	Overloading of antennas Affecting fault of design Fabrication detailing error	Collapsed at second panel
70m high at Horowpatana (Sri Lanka Telecom) *See Fig 4*	Four legged steel lattice structure, designed for 10sqm antenna area.	Due to direct hit by a Tornado Overloading due to large cable tray	Twisting around its own axis

Further details of the tower are given below.
Sections used - 100x100x8, 100x100x10, 60x60x5, 50x50x5, 65x65x6, 90x90x7, 60x60x6, 80x80x6, 45x45x5 angle sections.

Materials used- High tensile steel with yield strength 355 M Pa and mild steel with yield strength 255 M Pa.

Tower geometry was generated in SAP 2000 and sections and materials were assigned.Then the loads were assigned (*see Fig 5*) to the model according to test report and analysis and design check were performed. This particular tower was tested for twelve times for eleven loading conditions. All load conditions were given in the report. Some of the Loading conditions used in test are bolt slip test, right ground wire broken, normal condition with maximum vertical loading and normal condition with minimum vertical loading. Among these loading conditions, loading condition 2(right ground wire broken condition- lc2 - no failures occurred), loading condition 10(normal condition with minimum vertical load-lc10- L18 failed under compression), loading condition 11(failed leg (100x100x8 angle) in loading condition is replaced with larger section (100x100x10) -lc11- no failures) and loading condition 12(normal condition with maximum vertical load- lc12 - L16 failed under compression.) were selected to perform analysis with SAP 2000 and verify.

For further strength capacity check of the structure, design check option available in SAP 2000 was used. For this purpose BS 5950- 2000 code was used. SAP 2000 cannot analyse members of slender class. Therefore slender members have to be manually checked by calculating member capacity using either BS 5950 or BS 8100. In this tower case its leg members are falling under slender class. Therefore the capacities were calculated according to BS 8100.

For bottom panel leg, 100x100x8 angle section compression capacity is 456 kN and for

100x100x10 angle it is 564 kN (depends on member lengths). From analysis axial compression forces of 352 kN for lc2, 462.8 kN for lc10 and lc11 and 486.5 kN for lc12 were obtained for bottom panel critical leg.

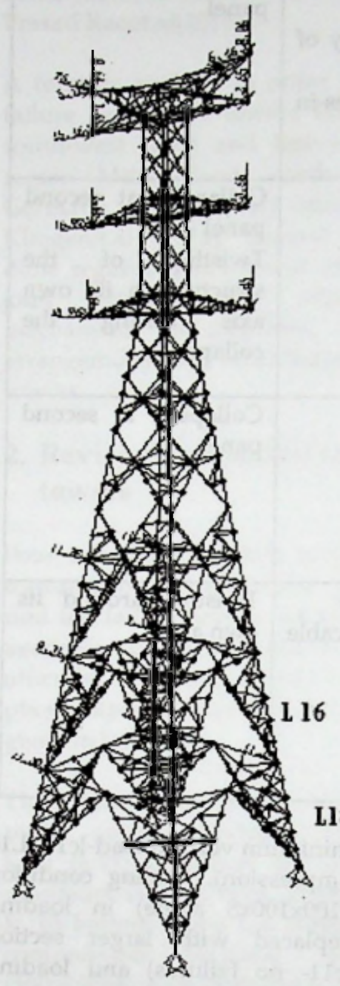

Fig 5Transmission tower geometry and failed legs

For second panel leg, 100x100x8 angle compression capacity is 416 kN. For second panel critical leg, compression force of 317.5 kN for lc2, 405.6 kN for lc10 and lc11 and 421 kN for lc12. Analysis results exhibited significant bending moment in all above cases (for both panel legs). So buckling is possible in critical case.

Above results clearly indicates the failure of same members under the same loading cases.

4. Erection and testing of model

Although, SAP 2000 full scale tower model predicted results exactly as the test results, to ensure the capability of SAP 2000 further, it was decided to construct a simple tower model and test it.

Aluminium was chosen as material to make the model, as it has low strength, so that failure loads might be quite low and it is easy to work on it (low hardness). A sample was obtained from an Aluminium section and tested using Haunsfield tensometer along with a strain gauge.

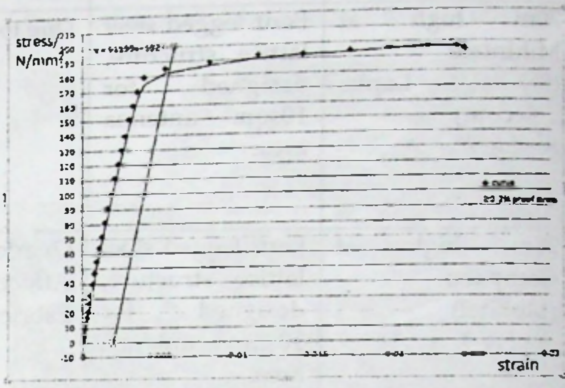

Fig 6Stress-strain curve obtained from test

From the results (*see Fig 6*) tensile yield strength, ultimate tensile stress and Young's modulus were found as 183 N/mm², 195 N/mm² and 51.2 kN/mm², respectively. Using the obtained mechanical properties a model generated with appropriate dimensions.

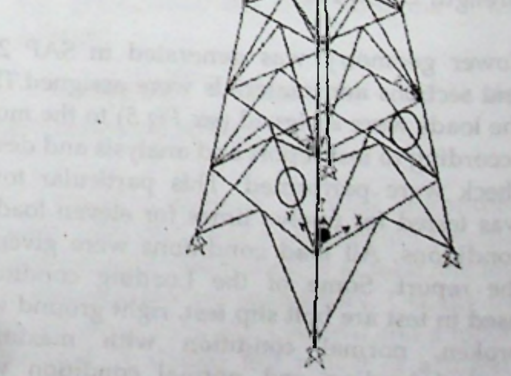

Fig 7Generated simple model and proposed loading and member failures

Suitable nodes were selected to be loaded and failure loads and failing members were identified (*see Fig 7*). Two nodes in legs were selected to apply horizontal force and two arm nodes were selected to apply a nominal quantity of both horizontal and vertical loads. From analysis and design check using SAP 2000 a force of 4.1 kN on leg nodes caused failure in second panel compression bracing, as shown in figure 7.

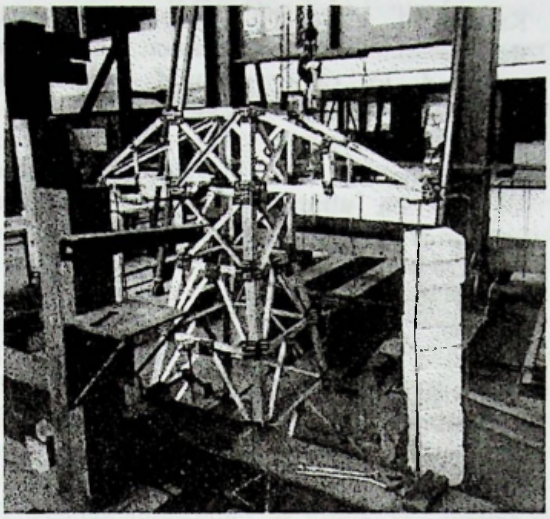

Fig 8Loading arrangement

Tests resulted in completely different failures. When load on leg nodes are increased to 3.5 kN second panel horizontal member got bent (*see Fig 10*) and third panel leg member got bent (*see Fig 9*).Loading procedure continued and second panel tension member bolts failed at the same load i.e. 3.5 kN.

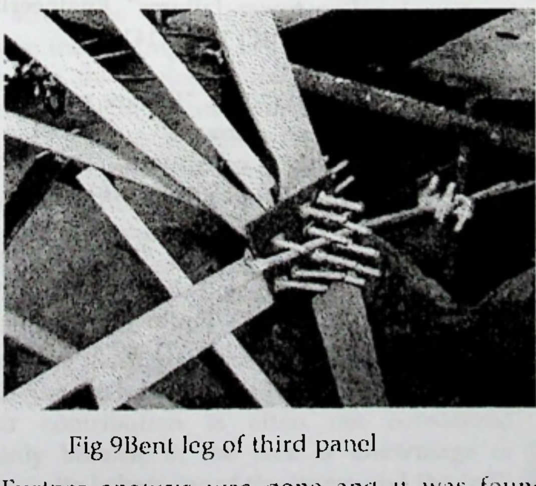

Fig 9Bent leg of third panel

Further analysis was done and it was found that yielding of bolts caused above bending failures. Due to bolt yielding, tension members were not effective. To stimulate this in SAP 2000, same model without those tension carrying members was generated and analysed. Results predicted failure of horizontal members and leg members, when load on leg node was 3.5 kN.The model without those tension members was further analysed to find the loads on leg nodes to cause the failure. When loads on leg nodes were increased to 2.5kN second panel horizontal members failed due to bending.

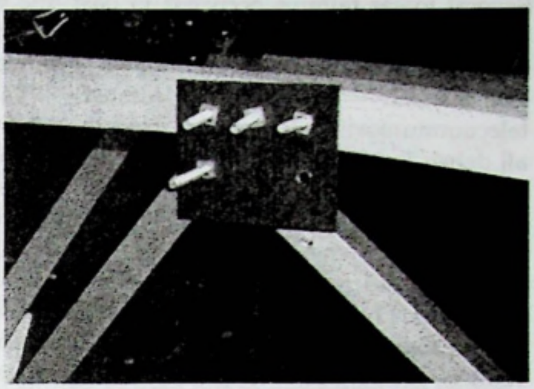

Fig 10Bent horizontal member and bolt failure

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Bolt shear capacity was tested with Hounsfield tensometer by pulling two steel plates fixed together by a single bolt. The failure occurred under a load of 3.6kN. This value was checked with the tension force induced in that bolt under failure load. Then whole model was analysed under actual failure load that is 3.5kN. A tension force of 3.28 kN was obtained in the failed connection. As the difference is not significant the cause was ensured.

5. Manual method to analyse 3D space truss

A manual method was developed by combining both tension coefficient method and unit load method.

Using above developed method forces of simple model was calculated and compared with SAP 2000 analysis results. Maximum variation was 8%, which is acceptable. So analysing 3D trusses with this method is acceptable.

6. Conclusion

Several tower failures occurred in past due to improper practice prevailing in both telecommunication sector and power transmission sector. Almost all telecommunication companies used to remove all debris immediately after a tower failure and produce a report that does not include detailed analysis of the failure, just to claim insurance. So up to now these failures were not deeply looked at and remaining a drawback in tower designing. Proper analysis of failures may lead to improvements in designing practices and reduce future tower failures. Mostly given reason for tower failures is tornados. If tornados are frequent in Sri Lanka, then amendments must be done to standard design wind speed being used for steel tower design. Nowadays most of the firms are overloading the towers with more antennas without getting approval from tower designer/consultant. This type of blind actions may lead to huge financial and resource loss due to resulting tower failures. So to find out the exact reason for the failure a complete technical analysis of towers failed is necessary.

In power transmission sector, towers are designed for transmission lines and a full scale test is carried out for the most critical tower arrangement of transmission line. This practice is there because of the complicated nature of steel towers. But several tower tests resulted in failure of main members which could have been avoided with a preliminary structural analysis checks. These checks can save much time, consultation cost and other resources.
Thus more improvements can be made in Sri Lankan tower designing industry by considering preliminary analysis methods. By making use of available structural analysis facilities (specialised programs/common programs) an effective design and efficient design process can be developed.

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