ENGINEER - Vol. XXXX, No. 02, pp. 07-12, 2007

Forensic Investigation on Design and Construction Failures

P.B.R. Dissanayake

Abstract: In this study, forensic investigations on several structural failures in Sri Lanka have been investigated. The reasons that led to failures of these selected case studies have been studied. In this context, method of forensic investigation includes structural analysis, Finite Element Modelling and material testing to some extent. With the outcomes of those analyses, real reasons for each failure have been explained. Furthermore, the responsibilities of some of the failures in these cases are highlighted. Finally, general conclusions are drawn from the study.

Keywords: Failure, design, construction, investigation

1. Introduction

Forensic investigation in structural engineering is meant to be the detailed studies of structures, usually after failure has occurred and having multi objectives. In fact, forensic investigation of structures was the actual reason for development of high rise buildings and marvellous bridges around the world as it taught designers the actual behaviour of structures under different scenarios. The interesting thing with forensic investigation is that it does not have a specific sequence of activities similar to the design stage. However, most of them undertake some type of structural analysis with differing magnitude and sometimes combined with laboratory testing.

Some important approaches to forensic investigations are given below:

1. Any cause of a failure is not assumed until all information is obtained, reviewed, and verified.
2. Independent information is obtained from sources not the initially used nor thought to be important.
3. The wider the range of information about an event is collected.
4. The investigation is not confined to a single investigative path during failure analysis by prejudging the cause of the failure.

The important qualifications of a forensic engineer are being expert in the subject under investigation and fair, impartial, and ethical (Truthful, Objective, Avoid conflict of interest)

Considering the Sri Lankan context, there were several design and construction failures that occurred in engineering projects in the past. However, considering recent information, there seemed to be more on design and construction failures in last decade. Forensic investigations of these failures were carried out for several design and construction failures to identify what were the actual reasons for these catastrophies. Such studies will help in understanding and eliminating similar situations in the future by our local engineers and designers.

In a construction project as with the guidelines of ICTAD [1, 2 & 3] (Institute of Construction Training and Development), there are several parties involved to perform a common task but with different perspectives. The consultant is hired by the client and, as such, his/her primary duty is to safeguard the interests of the client. This includes the realization of a satisfactory end product and achieving it within the specified time and cost. The consultant plays a vital role towards the satisfactory execution of the project.

In this paper, attention has been focussed to bring out some alarming trends in the construction industry of Sri Lanka, through some case studies, where the consultant and contractors have not performed their roles satisfactorily during the construction phase, thus becoming partly responsible for the failure.

Eng. (Dr.) ***P.B. R. Dissanayake****, C. Eng., MIE(SL), B.Sc. Eng. (Hons) (Peradeniya), M.Eng. (Ehime), Dr. Eng. (Ehime), Senior Lecturer in Civil Engineering, Department of Civil Engineering, University of Peradeniya.*

2. Case Studies

In this study several failures were investigated and following are given in detail,

- Steel Bridge failure at Paragastota.
- Roof truss failure at Polgolla.
- Telecommunication tower failure at Beliatta.

2.1 Steel Bridge failure at Paragastota

The bridge was originally constructed over Kala Oya in Anuradhapura in 1906 as a steel truss bridge and the then state of the bridge deck could not be found from available literature. In the 1965/66 period, it was removed from there and reconstructed in Paragastota by the Public Works Department. At this time, the bridge deck was covered with wooden planks. Subsequently, in the 1989-1990 period, on top of the timber deck, an in situ reinforced concrete deck was laid to a thickness of 150 mm. It appeared that in casting the RCC deck a substantial part of the timber planks of the old deck had been used as the formwork. The bridge was located in an area where a number of stone pits was present. It collapsed on the 10th July 1999 afternoon when a tipper, reported to have been carrying about 5 cubes of metal, was crossing the bridge. Failure state of the bridge is shown in Figure 1 below.

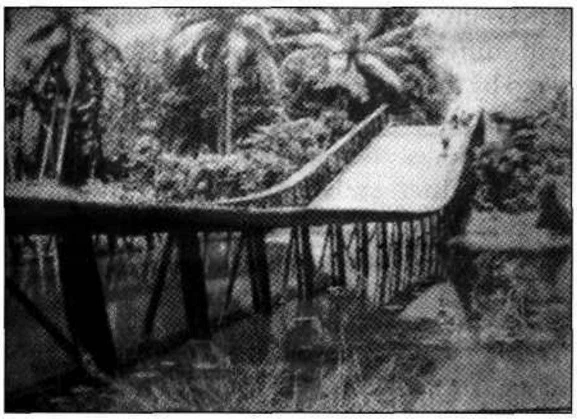


Figure 1: Failed bridge at Paragastota

2.1.1 Material testing

Bridge material on truss was tested to identify the kind of steel used for truss members. Using comprehensive laboratory testing, material parameters such as yield strength, tensile strength and Young's modulus of the bridge deck material were found. To identify the type of steel used, microscopical examination of samples of bridge deck material was performed. From these, it was understood that the type of bridge material was a kind of steel having a high percentage of Carbon compared to those used at present.

2.1.2 Structural Analysis

To understand the failure of the bridge, a Finite Element Model of the bridge was prepared using SAP90 structural analysis software. Truss members were modelled as 3D frame elements. Furthermore, material parameters obtained from laboratory testings were put into the above model. From this structural analysis, it was found that the member force of the bottom chord member at mid-span is exceeding the elastic capacity when the 25 tonne tipper passes over the bridge. In other words, some members are likely to deform plastically when subjected to the above moving load. However, as the load is moving, the high tensile force is present over a small period of time, this preventing the progressive collapse of the structure in the first instance. Nevertheless, this will produce an irrecoverable deformation in the member. This is likely to cause a sag in the truss. With a the similar effect from the other members, forces are likely to change along with some other member forces also exceeding the elastic capacity. From the analysis it is evident that the failure was triggered by the yielding of the bottom chord members, resulting in large deformation, with consequent yielding and fracture of diagonal members [4]. Table 1 shows the summary of the findings.

Table 1- Summary of the findings

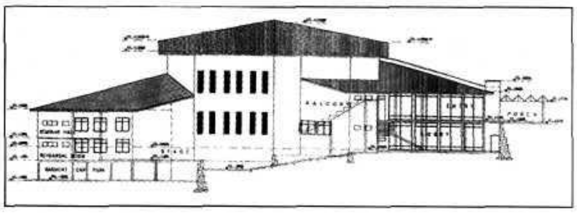
Member	Applied load due Dead and Imposed loads / (kN)	Elastic capacity / (kN)
Critical bottom chord member (Member No 17)	-1950	1870
Critical diagonal member (Member No 235)	540	600

In this context, the construction sequence could not make a significant contribution to the failure of the bridge. In the 1989-1990 period, when the bridge was altered with a concrete deck slab, other structural components were left as they were and thus the failure attributes from heavy loading on the bridge.

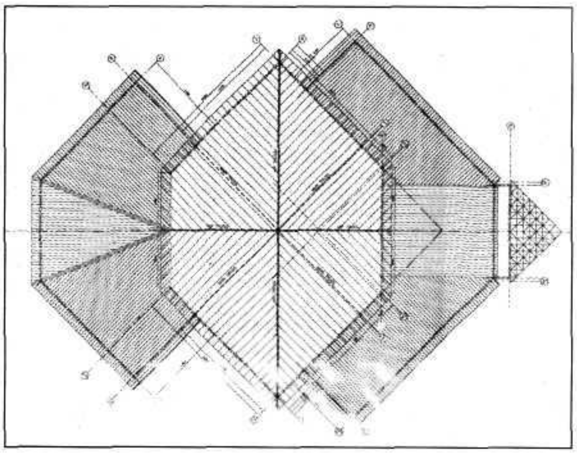
If the bridge was analysed before altering the timber deck to a concrete deck, this tensile stress increase could have been noticed and necessary alterations could have been done. Analysing all bridges in the national road network is not required. Indeed, such a methodology would be costly. However, there are needs to analysis bridges, which seem to carry heavy loads to avoid failures like in the Paragastota bridge.

2.2 Roof Truss Failure at Polgolla

This case involves the construction of an auditorium, having a reinforced concrete structure with an asbestos roof, supported on steel trusses forming a dome type frame. Figure 4 shows the elevation and plan of the building.



(a)Elevation



(b) Plan

Figure 4. Elevation and plan ofthe auditorium

The central part of the roof has a hexagonal plan, and the steel frame which supports it consists of 8 primary trusses supported on concrete columns at their far ends and connected together to a central hub at their common ends as shown in Figure A.1. page 12 In this Figure, circles and numbers inside indicate the construction sequence of trusses.

These 8 trusses are of three types (Figure A.1). Four main trusses of Type TR6 each of span 15.575 m, two shorter hip trusses of Type TR4 each of span 14 m, and two longer hip trusses of Type TR5 each of span 22.25 m. Several shorter secondary trusses (not shown) are connected to the hip trusses and the roof purlins, supporting the asbestos sheets, are laid on these trusses. A 3D finite element model used to analyze the truss system is shown in Figure 5

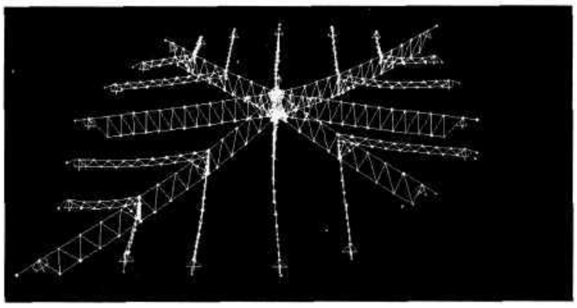


Figure 5. Finite Element Model of the Truss System

The top and bottom chords of the trusses are double channels and the webs are double angles. They are welded to gusset plates except at the central hub, where they are bolted to gusset plates which are welded to the central hub. At their supports on RC column tops (Figure A.1), four trusses are fixed (pinned) with angle cleats welded to gusset plates of the trusses and bolted to rag bolts and placed on a shoe plate at the column top. The other four truss supports are made free (sliding), with slotted holes in the angle cleats, which are free to slide on shoe plates.

In this construction, the contractor was selected by the consultant and, after the contract had been awarded the truss design had been changed to a more complicated one from the original simpler design and the Contractor, who did not have any previous experience in constructing such roofs, had indicated some reservations regarding the construction according to the final design. However, he finally agreed to do the construction according to the complicated design.

2.2.1 Construction sequence

Referring to Figure A.1, the construction sequence followed by the Contractor was as follows:

a. Assemble the two main Trusses (TR6-1, & TR6-2), on the ground, connect them to the central hub, and raise the connected pair into position with a crane, and support their far ends on the columns.

b. While the crane holds the above pair of trusses, lift main truss TR6-3 into position using another crane and fix it to the hub and to the column support. Remove the second crane, while the first crane is still holding trusses TR6-1, & TR6-2.

c. Lift the other main truss (TR6-4) into position using the second crane and fix its two ends to the hub and the column.

d. Remove both cranes and leave the four main trusses (TR6-1, TR6-2, TR6-3, & TR6-4) supported at the ends and connected to the hub at the centre.

e. Using a crane lift the shorter hip truss TR4-1 into position and connect it to the hub and the column support. Remove the crane.

f. Using the crane, lift the truss TR4-2 to position and connect it to the hub and the column support. Remove the crane.

g. Using the crane lift the longer hip truss TR5-1 into position and fix it to the hub and the column. Remove the crane.

h. Using the crane lift the other hip truss TR5-2 into position and fix it to the hub and the column support.

The Steps a to d above were completed within 2 days and the four TR6 trusses were left standing for almost a month before the Steps e & f were completed (within 2 days). Two days after Steps f and g were attempted, the failure occurred.

2.2.2 Failure of the truss system

Wobbling of the trusses had been noticed during the roof construction but positive steps to prevent it had not been taken. Cables have been used to tie top chords to prevent wobbling, but this has not been very effective for obvious reasons.

When the first TR5 truss (TR5-1, one of the longer hip trusses), was put in place, wobbling had been very noticeable. Later, the second TR5 truss (TR5-2) was hoisted with the crane, using two belts attached to the truss, and two cables were used to tie the upper chord of the truss to the two main trusses on either side. After lifting the truss to position a connection had been made at the centre to the hub. Afterwards, in order to make the end support connection (to the column), the crane operator had released the belts. While this was being done the belt nearer to the centre had snapped and the collapse occurred, while the outer end of the TR5-2 truss was still in the air, held by the crane.

Figure 6 shows the collapsed truss system, and Figures 7 & 8 show some examples of very poor workmanship and violation of specifications, when making connections at supports.

Figure 6. Collapsed truss system

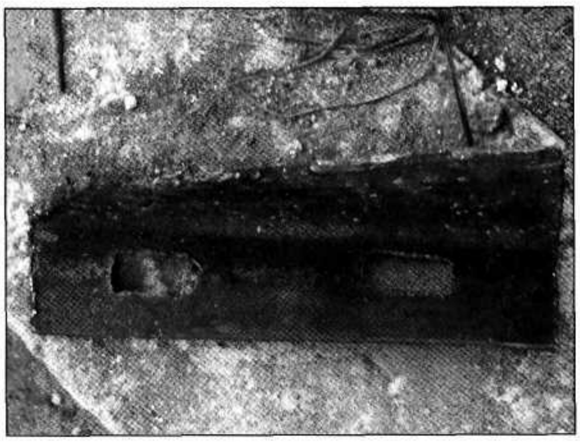


Figure 7. Flame Cut Angle Bracket

Figure 8. Poor Connection at Shoe Plate

2.2.3 Consultant's lapses

Investigation into the failure revealed that the Consultant had not given clear instructions to the Contractor regarding the construction procedures, even though the Consultant knew that the Contractor lacked relevant experience. Finite element analysis of the truss system (Figure 6) showed that the truss sub-systems used during the construction phase were not stable, because they were not adequately supported against out of plane buckling. The wobbling of the trusses experienced during construction, and the final failure was due to this. If an experienced engineer was present at the site during construction, he/she would have noticed these. Even though the Consultant had visited the site many times during the roof construction, poor quality of the work had not been reported, and the work had been allowed to continue.

However, before the failure, and after the Steps a to f had been completed, the Consultant had approved payment for the work, without making a proper check to see whether the work was up to the standards specified. A cursory glance would have detected the poor workmanship, and the vulnerability of the inadequately supported frame system.

It was obvious that the Contractor had not done the work in accordance with Specifications, but it was also very clear that Activities 5, 6, 8, 9, 11, & 13 (Section 2 of ICTAD) had not been properly carried out by the Consultant.

2.3 Telecommunication tower at Beliatta

This tower was constructed in Beliatta having a design height of 70 m and it had four leg-legs of

Figure 9: View of the collapsed stage of the tower

angle-iron type. The tower has been designed for steel antenna towers and antenna sporting structures. When it was constructed to a height of 60 m, the tower collapsed suddenly without any warning. Figure 9 shows the collapsed stage of the tower.

2.3.1 Tower Analysis

In order to determine the cause of the tower collapse and to check the final tower design, analyses of the tower system was carried out using the general-purpose finite element package SAP2000 [1].

Behaviour of the tower system during the construction stages was studied using two finite element models. The members of the tower were modelled using 3D FRAME elements. As such, two Finite Element models were prepared for the collapsed stage and design stage. Loading applied to these models were self weight, wind loading and a combination of self weight and wind load was considered. From these analyses, the following summary and conclusions were drawn.

2.3.2. Summary and Conclusions

1. Compression and tensile forces in members are below the allowable limit of every section for the final design stage as well as for the collapsed stage.
2. At the construction stage, horizontal bracings have not been provided. However, the presence of horizontal bracings is very important since they reduce effective lengths of members and twisting also.
3. Local buckling check was carried out for the collapsed model.
4. All members are satisfied apart from some of the horizontal members.
5. In any connection, if bolts are not properly fixed, it will tend to transfer additional moments to the tower.
6. At the construction stage, the top part (final 10m) of the legs was erected as single angle. Furthermore, there are no bracings at the top part (final 5m). Therefore, the deflections are induced from there.

In structures of this nature, construction sequence and method of construction have a significant effect on the stability of the structure. In this situation, the Consultant supervised the construction work of the tower. Considering the results obtained, it can be concluded that the design of the tower is safe. With reference to notes 3, 4 and 5 mentioned above, the collapse of the tower occurred as a combination of local buckling behaviour at the construction stage and the conditions mentioned in note 4 and 5.

This failure could have been avoided if the proper construction procedure was given. As with ICTAD guidelines, it is the duty of the Consultant to see the sequences of the construction procedure. As with the general agreement of engineers, how sound a design is it will not be useful if the correct sequence of construction is not followed.

3. Conclusions

Based on case study results, following general conclusions have been made.

- It is the primary duty of the consultant to follow proper procedures and safeguard the interests of the client by properly advising the contractor and the client.
- Consultants not playing the intended role can lead to failure in the construction projects.
- Inexperience of the contractor also contributes to these failures, and the client also is to be blamed for not selecting the proper consultant.
- Construction sequence is an important part and so is the rechecking of the design for these sequences.
- Any modifications or alterations of structures must be re-analyzed.

4. References

1. Scope of Consultancy Services, ICTAD Publication 110: ICTAD/CONSULT/04, Ministry of Housing and Construction.

2. Client Guide - Selection of Consultants, ICTAD Publication 110: ICTAD/CONSULT/03; Ministry of Housing and Construction.

3. ICTAD Specification for Building Works (1980) Institute for Construction Training and Development, Colombo, Sri Lanka.

4. Dissanayake, U. I. Failure of Paragastota steel bridge, (2000), proc. Annual sessions, IESL Central Province.

5. BS 8007: 1987- Design of concrete structures for retaining aqueous liquids.

6. Ranaweera, M. P. and Dissanayake, P. B. R. Consultant's role in the construction phase of a building project, (2005), proc. Annual sessions, IESL Central Province.

5. Appendix

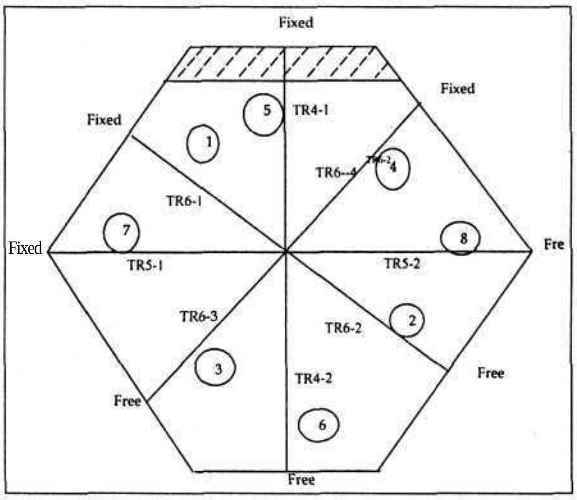


*Figure A.1: T Roof Plan Showing Primary Trusses and Construction **Sequence***