CANTILEVERED TRUSSES FAILURE ASSESSMENT

Ir. Emmy Sherina Ismail Hashim

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Cantilevered Trusses Failure Assessment

Introduction

Cantilevered Trusses Failure Assessment - Chronology

- 2011 — Trusses Constructed
- 2015 — Failure of Trusses
- 2018 — New Trusses Built

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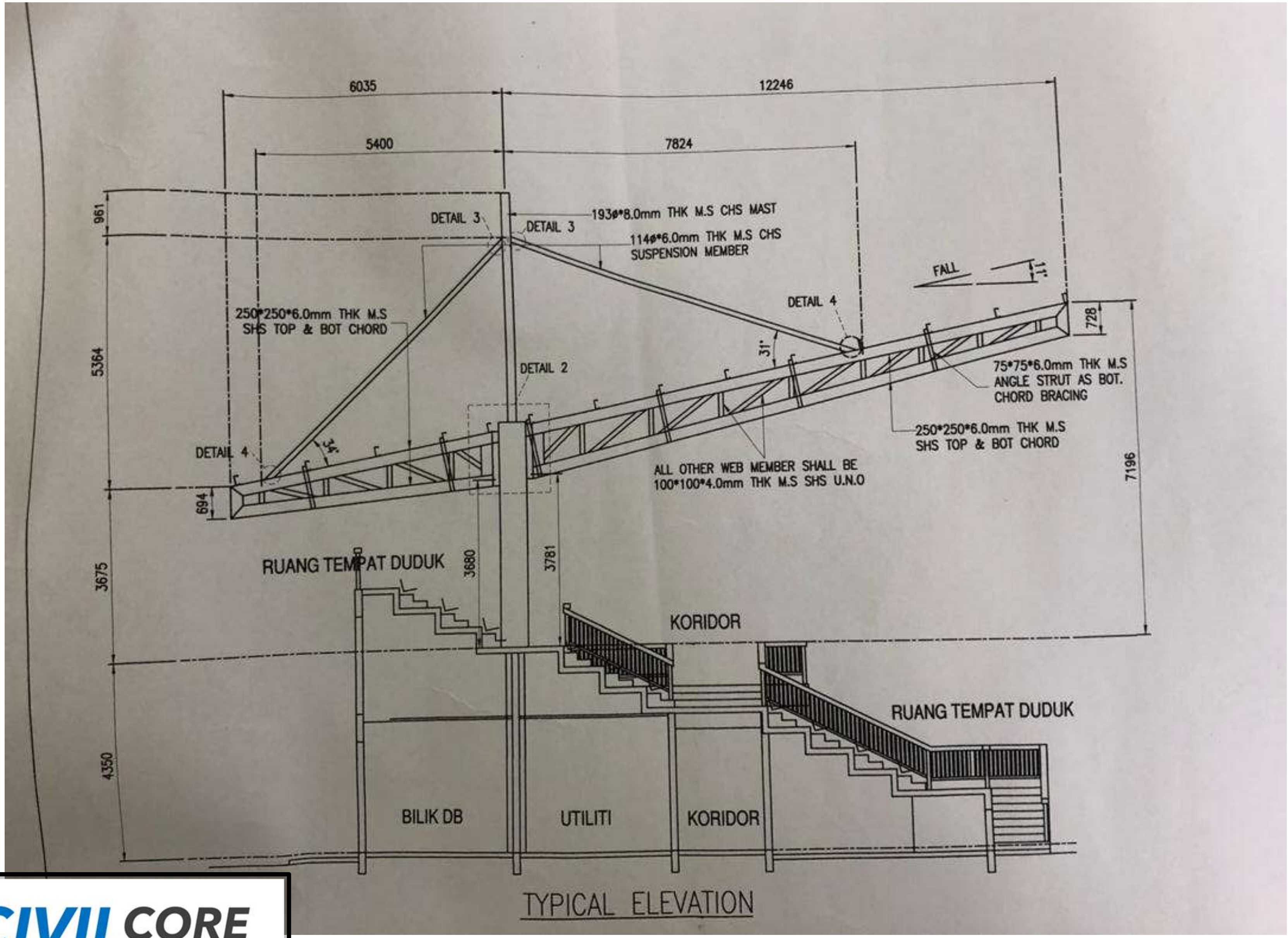

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Cantilevered Trusses Failure Assessment

-Introduction

- Contractor changed the roof trusses design during construction, approval given by S.O. for this was a design and build project

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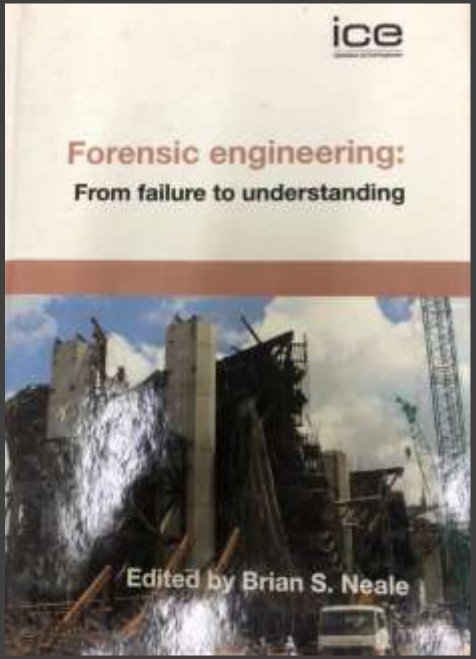
Literature Review



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-LITERATURE REVIEW

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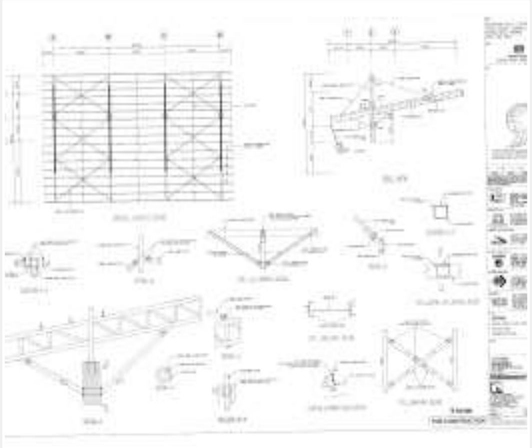
Research Methodology

<u>Cantilevered Trusses Failure Assessment</u> **Research Methodology**

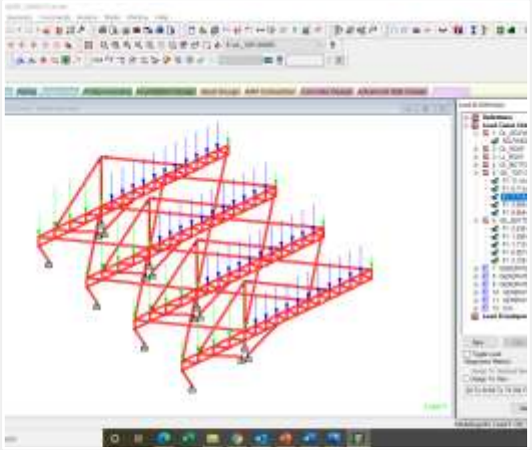


1st Step

Desk Study

2nd Step

Site Investigation



3rd Step

Back Analysis

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Cantilevered Trusses Failure Assessment

Research Methodology – Desk Study

Collection of information regarding the project

Checking of as-built drawings and construction drawings

Preparation of tools for inspection purposes

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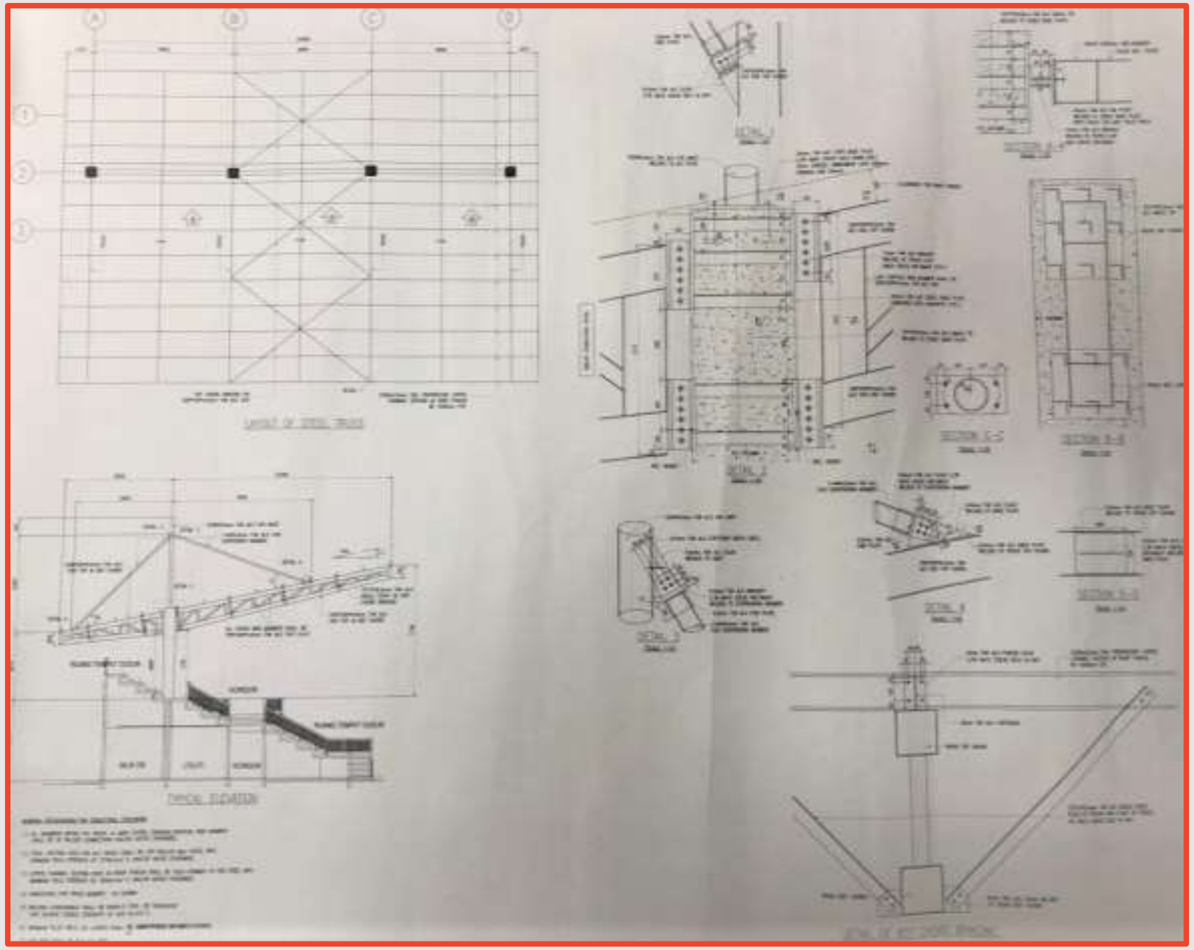
Research Methodology – Desk Study



Construction Drawings

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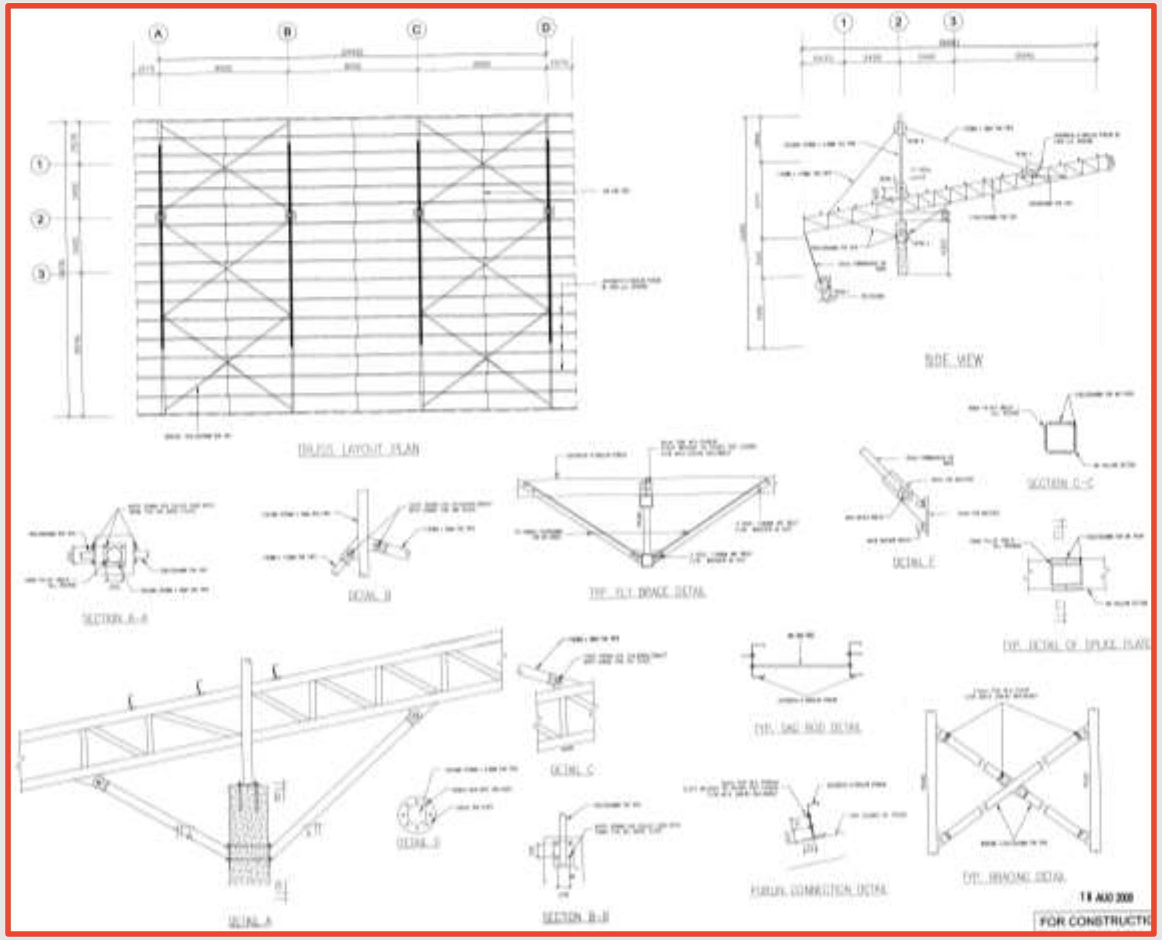
Research Methodology – Desk Study



Revised Construction Drawings

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Research Methodology
– Site Investigation

To investigate construction complying to as-built drawing

To interview personals at site on failure process

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RESEARCH METHODOLOGY

– SITE INVESTIGATION

Debris at site tells a lot about how the structure fails. It is of paramount importance not to move any parts of the fallen structure for investigation.

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Research Methodology – Site Investigation

- Site investigation normally checks on these items:-
  - The position of the collapse roof to find the epicenter of failure
  - Measurement of member sizes and thickness, plate size and thickness, diameter of bolts
  - Measurement of bolt embedment length
  - Measurement of bolt location, edge distances
  - Non-destructive testing (Rebound hammer) to concrete surface
  - Measurement of splice and weld sizes
  - Any other structural distress on remaining structure

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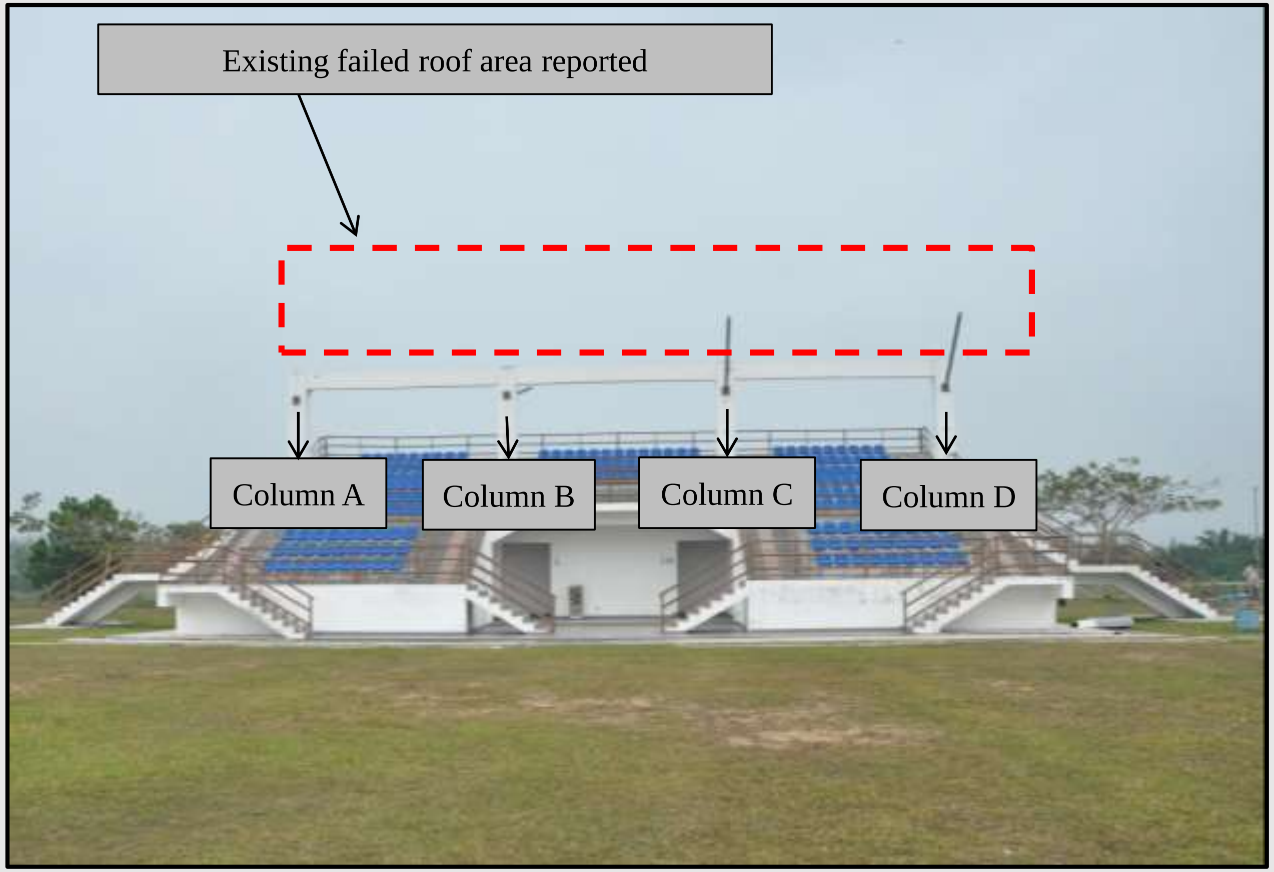
Research Methodology
– Site Investigation



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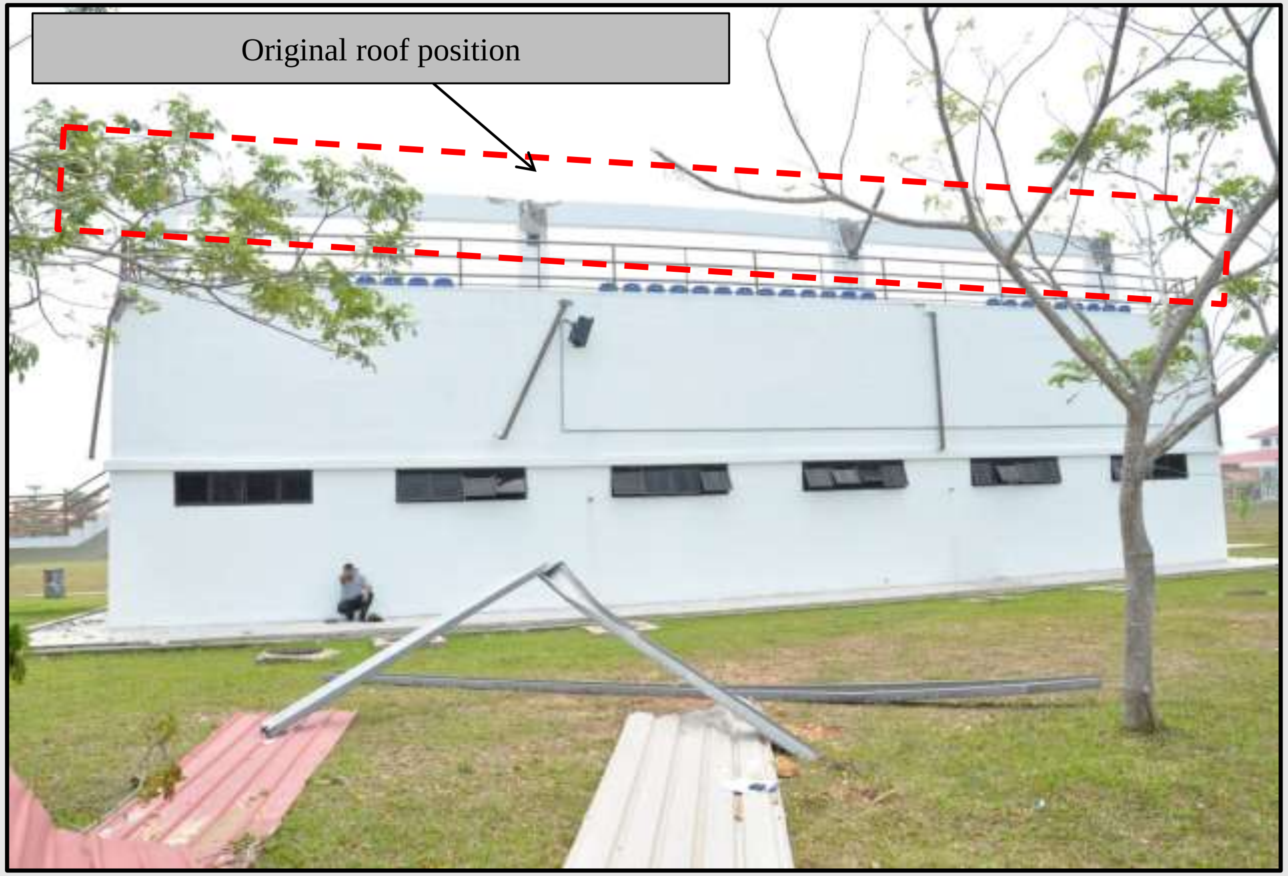
Research Methodology
– Site Investigation



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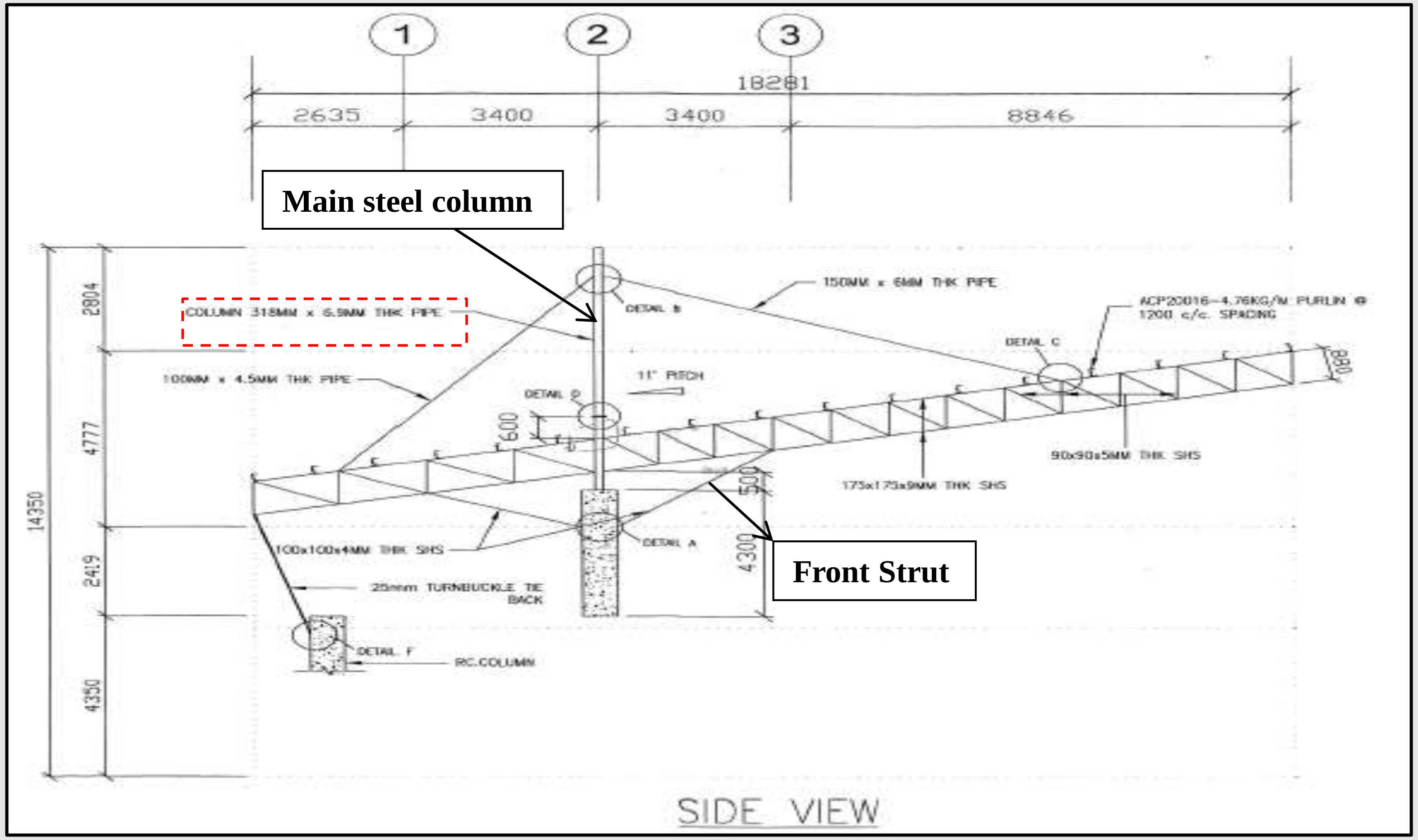
Research Methodology
– Site Investigation

Cantilevered Trusses Failure Assessment

Research Methodology
– Site Investigation



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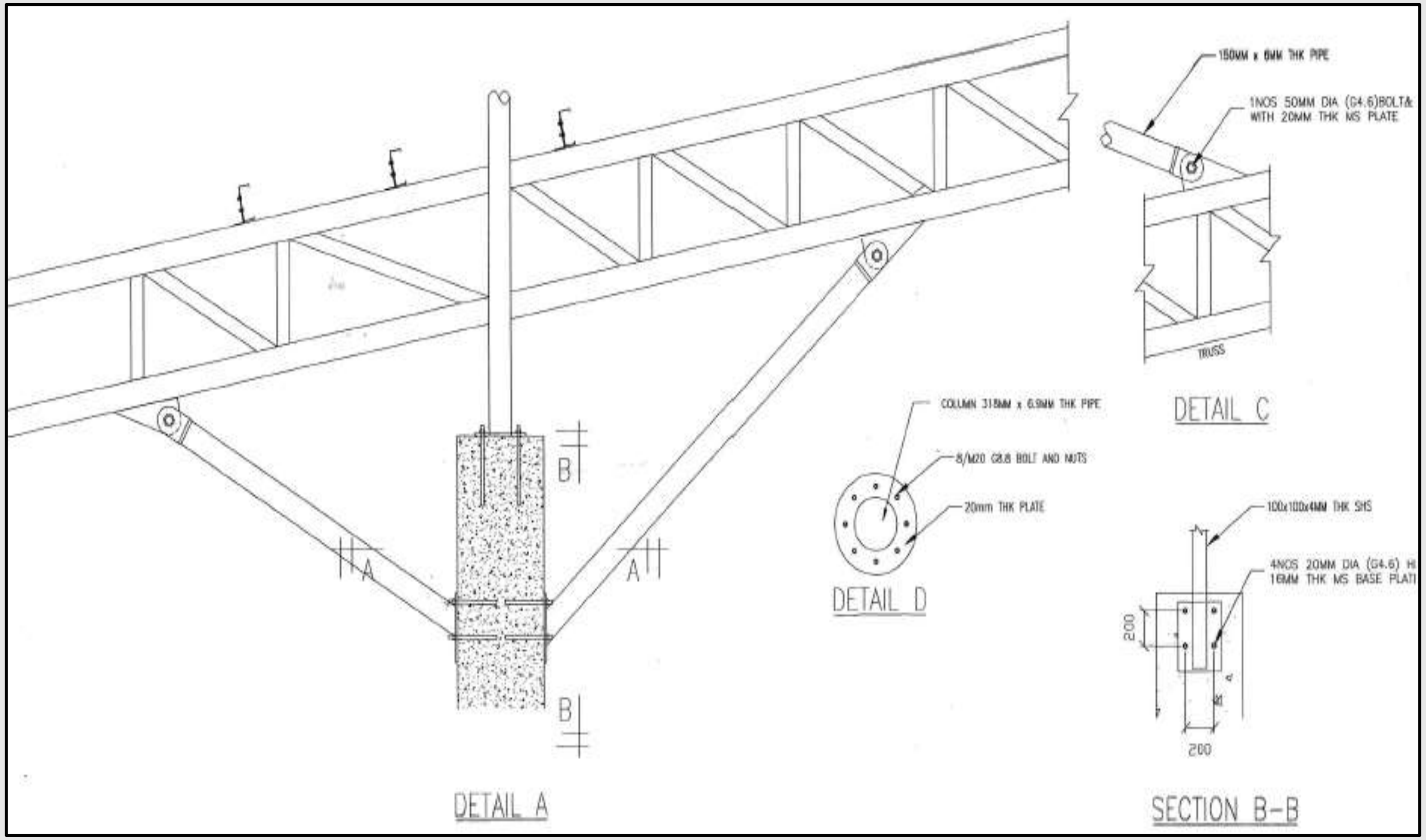
Research Methodology
– Site Investigation



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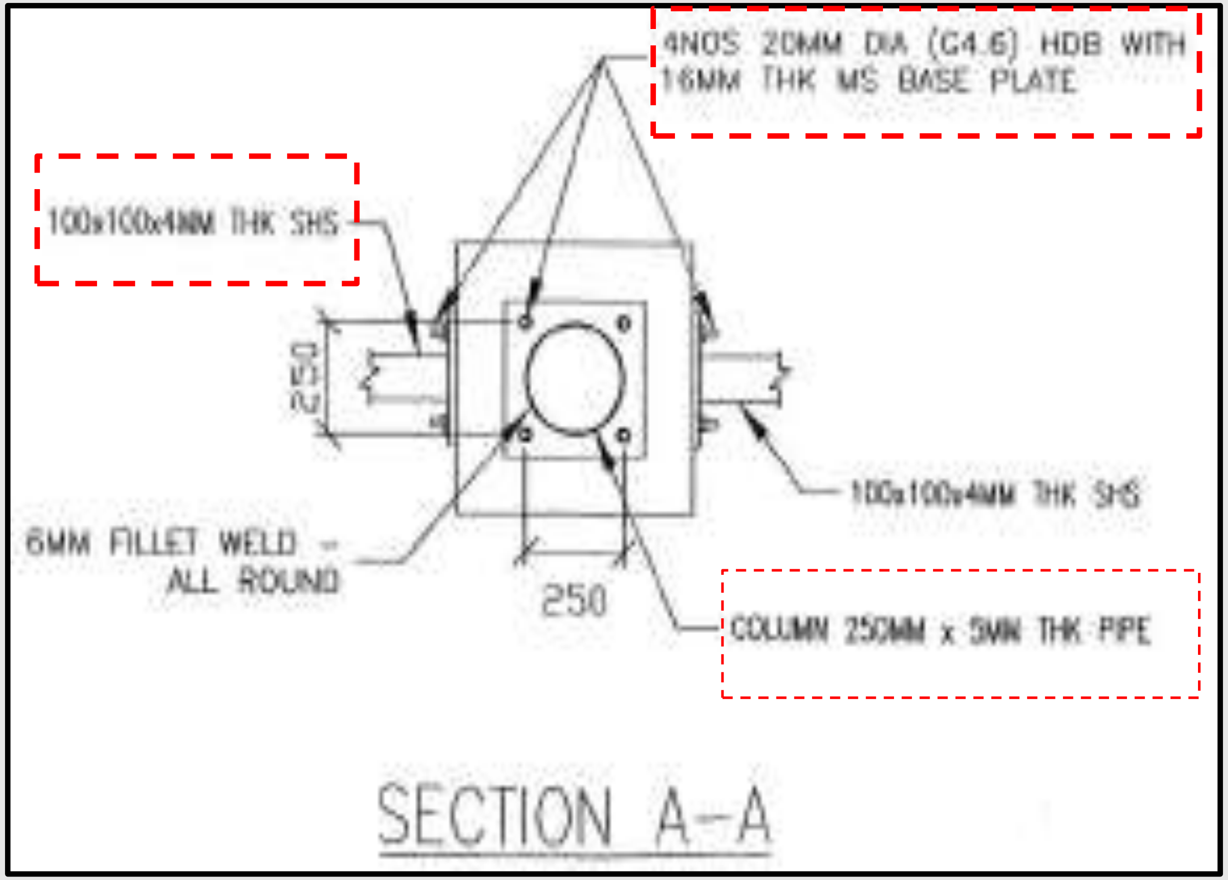
Research Methodology
– Site Investigation



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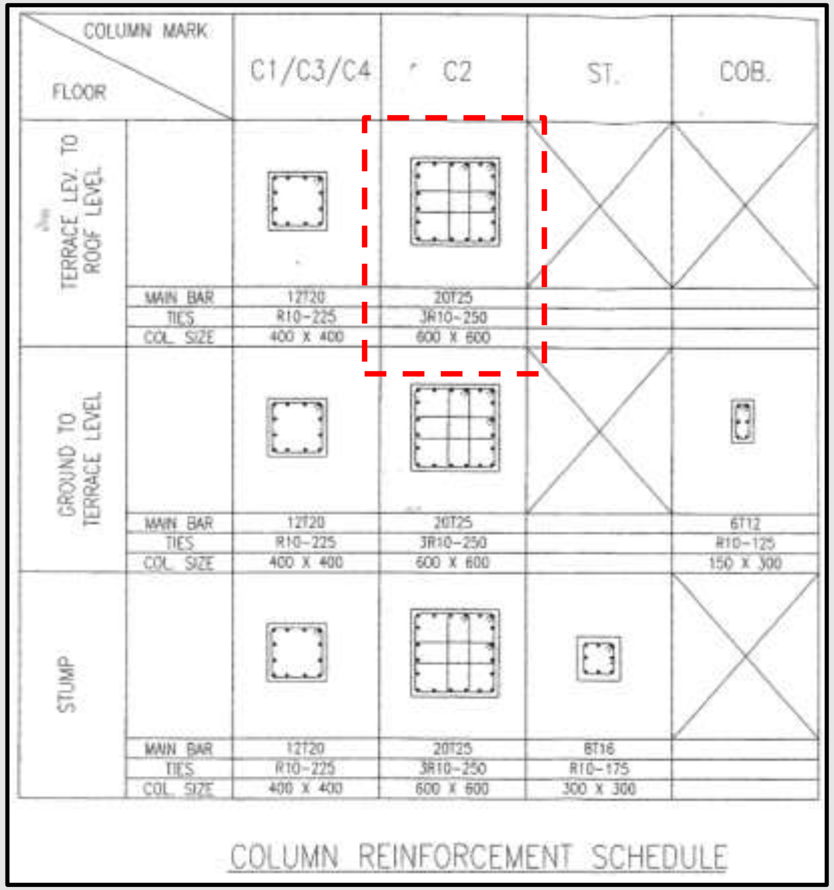
Research Methodology
– Site Investigation



FLOOR \ COLUMN MARK		C1/C3/C4	C2	ST.	COB.
TERRACE LEV. TO ROOF LEVEL	MAIN BAR	12T20	20T25		
	TIES	R10-225	3R10-250		
	COL. SIZE	400 X 400	600 X 600		
GROUND TO TERRACE LEVEL	MAIN BAR	12T20	20T25		6T12
	TIES	R10-225	3R10-250		R10-125
	COL. SIZE	400 X 400	600 X 600		150 X 300
STUMP	MAIN BAR	12T20	20T25	8T16	
	TIES	R10-225	3R10-250	R10-175	
	COL. SIZE	400 X 400	600 X 600	300 X 300	

COLUMN REINFORCEMENT SCHEDULE

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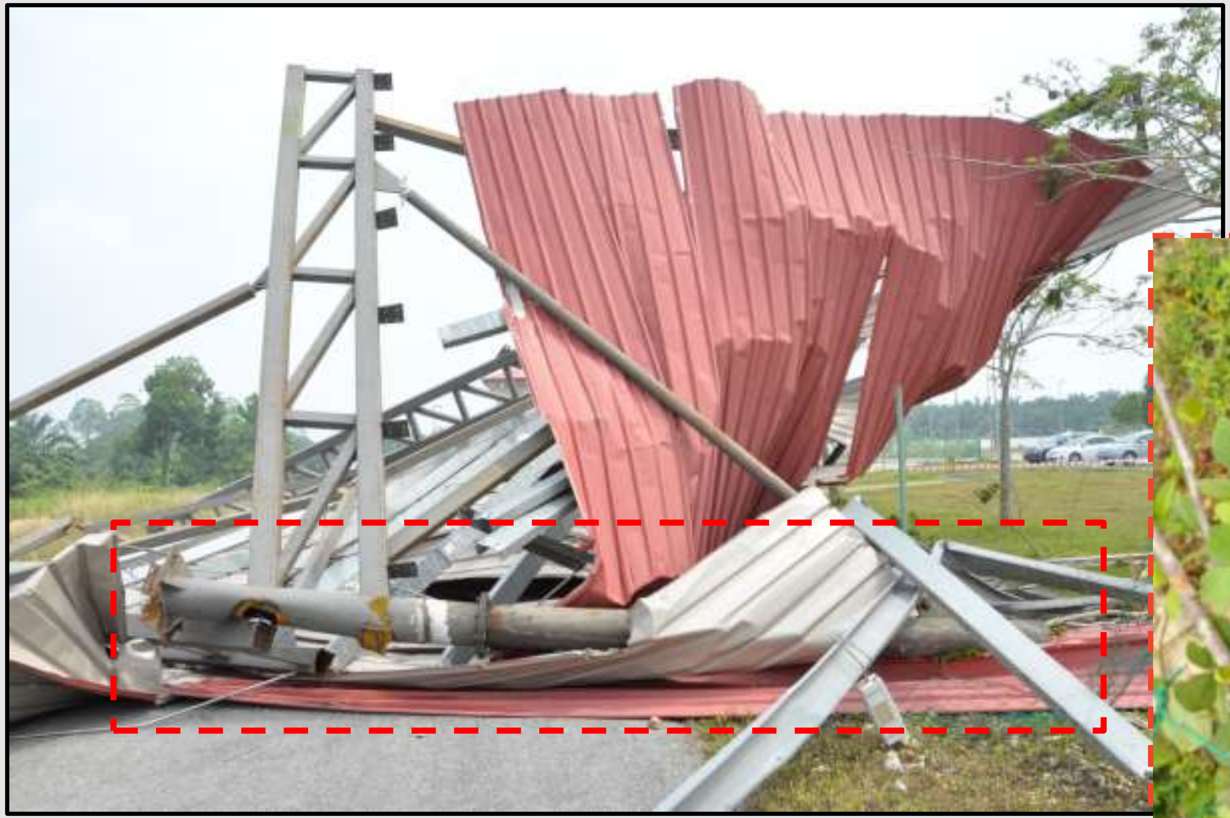
Research Methodology – Site Investigation



Column size 268.14mm vs 318 mm in drawings

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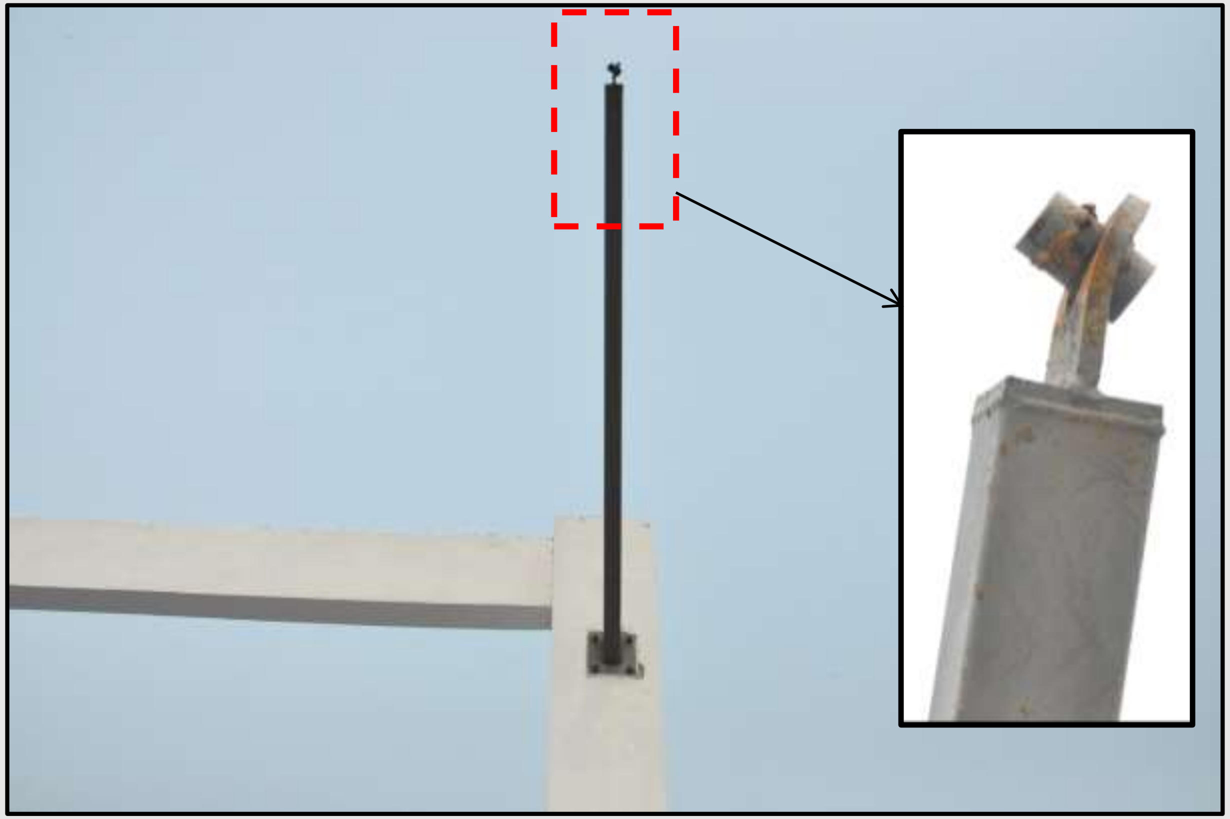
Research Methodology
– Site Investigation



Front strut size was 99.8 mm with 2 mm thickness vs 100 mm with 4mm thickness in construction drawing

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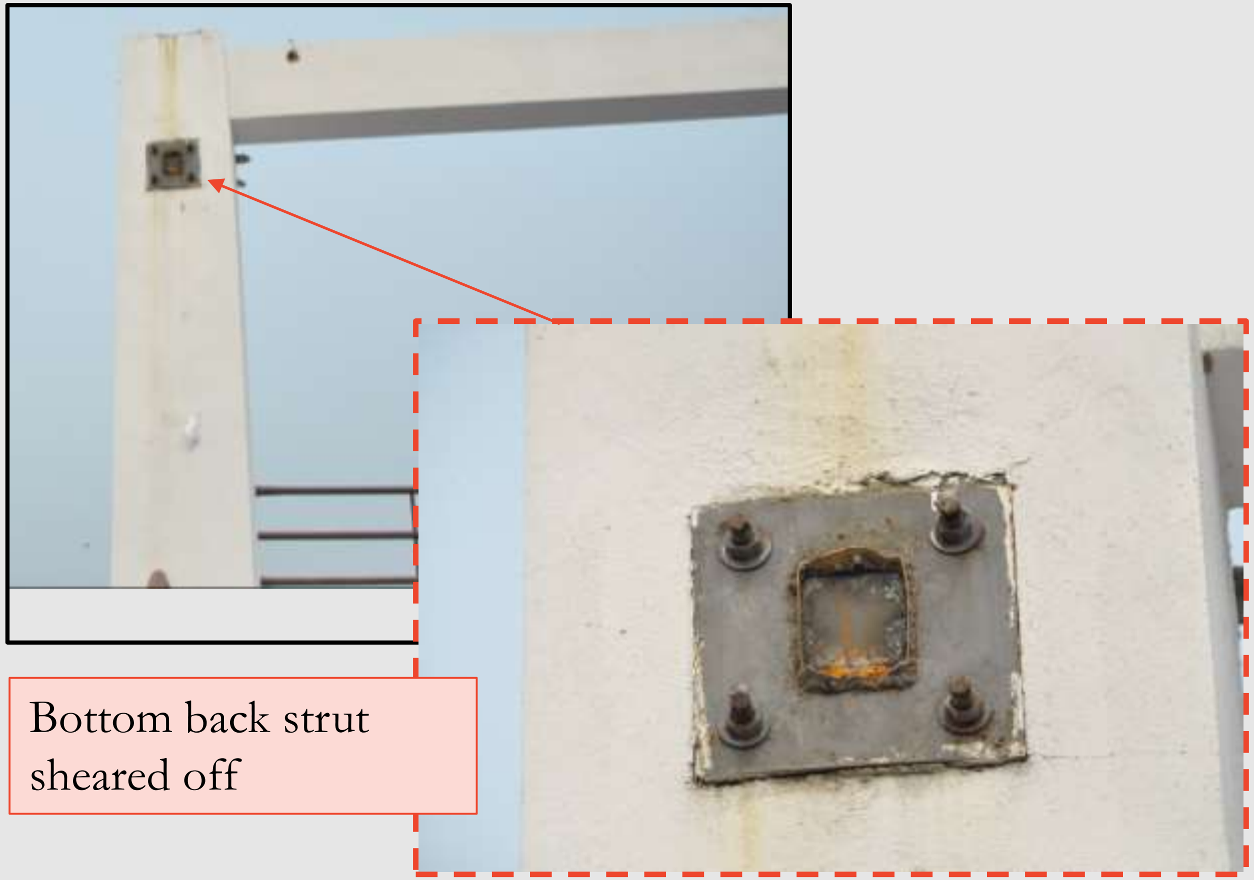
Research Methodology
– Site Investigation

No shear links at
top of column



Bottom back strut
sheared off

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Research Methodology – Site Investigation

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Cantilevered Trusses Failure Assessment

Research Methodology
– Site Investigation

20mm diameter Type 1 Deformed Bars were used as anchorage

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Research Methodology
– Site Investigation

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Research Methodology
– Site Investigation

Cantilevered Trusses Failure Assessment

Research Methodology
– Site Investigation

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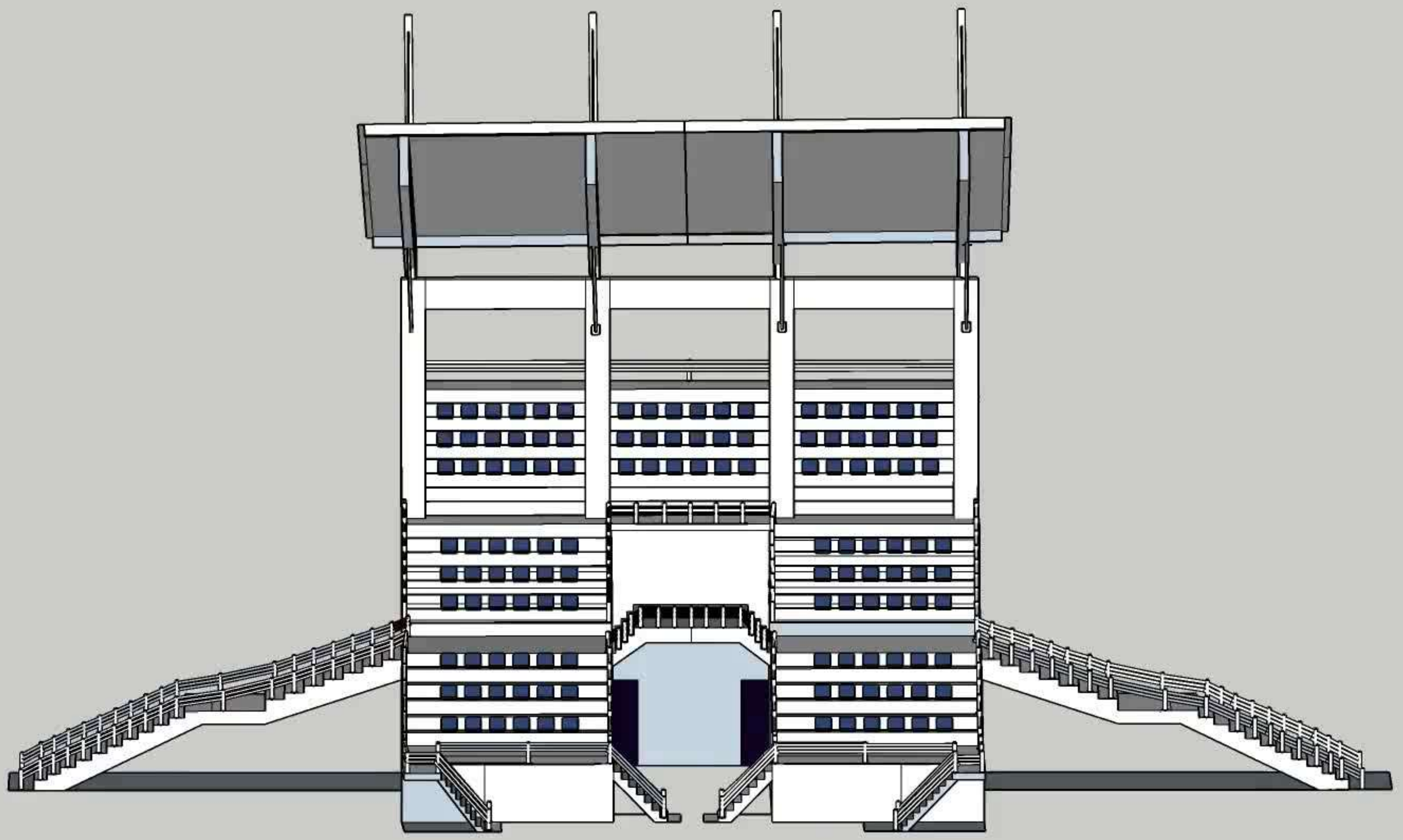

Cantilevered Trusses Failure Assessment

Research Methodology – Back Analysis

To model structure as per construction at site

To calculate reactions at connection of steel to concrete

To check stress in member and suitability of member sizes

Cantilevered Trusses Failure Assessment

Research Methodology

– Back Analysis

Procedures for determination of wind actions, W on the structure as tabulated in MS 1553 : 2002 are as follows:

Site wind speed determination;

i) Design wind speed determination from site wind speed;

ii) Design wind pressures and distributed forces determination; and

iii) Wind actions calculations.

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Figure 3.1 from MS 1553 showing Basic Wind Speed for Peninsular Malaysia

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RESEARCH METHODOLOGY

– BACK ANALYSIS

Table 4.1. **Terrain/height multipliers for gust wind speeds in fully developed terrain. Serviceability limit state design and ultimate limit state**

Height (z) m	Multiplier ($M_{z,cat}$)			
	Terrain Category 1	Terrain Category 2	Terrain Category 3	Terrain Category 4
≤3	0.99	0.85	0.75	0.75
5	1.05	0.91	0.75	0.75
10	1.12	1.00	0.83	0.75
15	1.16	1.05	0.89	0.75
20	1.19	1.08	0.94	0.75
30	1.22	1.12	1.00	0.80
40	1.24	1.16	1.04	0.85
50	1.25	1.18	1.07	0.90
75	1.27	1.22	1.12	0.98
100	1.29	1.24	1.16	1.03
150	1.31	1.27	1.21	1.11
200	1.32	1.29	1.24	1.16
250	1.34	1.31	1.27	1.20
300	1.35	1.32	1.29	1.23
400	1.37	1.35	1.32	1.28
500	1.38	1.37	1.35	1.31

NOTE. For intermediate values of height z and terrain category, use linear interpolation.

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RESEARCH METHODOLOGY

– BACK ANALYSIS

Cantilevered Trusses Failure Assessment

Research Methodology

– Back Analysis

Determination of Site Wind Speed

The site wind speed, V_{sit} was calculated using the formula below, as stated in Clause 2.2:

$$\mathbf{V_{sit} = V_S (M_d)(M_{z,cat})(M_S)(M_h)} \quad \text{.........................(1)}$$

where

- V_S = 33.5 m/s for Zone I as shown in Figure 3.1 of MS 1553 (Figure 9)
- M_d = 1;
- $M_{z,cat}$ = 1.16 for terrain/height multiplier taken as Category 1 : Exposed open terrain with few or no obstructions for 15m height of structure (Refer to Table 1);
- M_h = 1 for hill shape multiplier;
- M_S = 1 for shielding multiplier.
- V_{sit} = (33.5) (1) (1.16) (1) (1) = 38.86 m/s.

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RESEARCH METHODOLOGY

– BACK ANALYSIS

Importance Factor from Table 3.2 of MS 1553

Nature of Occupancy	Category of Structures	*I*
Buildings and structures that represent low hazard to human life in the event of failure such as agricultural facilities, temporary facilities and minor storage facilities.	I	0.87
All buildings and structure except those listed in category I, III and IV.	II	1.0
Buildings and structures where the primary occupancy is one in which more than 300 people congregate in one area.	III	1.15
Essential buildings and structures Hospital and medical facilities Fire and police stations Structures and equipment in civil defense Communication centres and facilities for emergency response Power stations and other emergency utilities Defense shelter.	IV	1.15

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Research Methodology

– Back Analysis

Determination of Design Wind Speed

The design wind speed, V_{des} was calculated using the formula below, as stated in Clause 2.3:

$$\mathbf{V_{des} = V_{Sit}\ (I)} \text{ ....(2)}$$

where

- $V_{Sit} = 38.86$ m/s
- I = 1 for non essential structure in which less than 300 people congregate in one area (Table 2);

$$V_{des} = (38.86)\ (1) = 38.86 \text{ m/s}$$

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Research Methodology

– Back Analysis

Determination of Design Wind Pressure

The design wind pressure, p was calculated using the formula below, as stated in Clause 2.3:

$$\mathbf{p = (0.5\ \varrho_{air})\ (V_{des})^2 (C_{fig})(C_{dyn})\ Pa \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)}$$

where,

- ϱ_{air} = density of air which was taken as 1.225 kg/m^3;
- V_{des} = 38.86 m/s
- C_{fig} = aerodynamic shape factor from equation
  $C_{fig} = 5.0\ (1 - x/L)$; x is distance from the ledge of the cantilevered structure
- C_{dyn} = 1 (beams less than 15m long).
- p = (0.5 x 1.225) (38.86)^2(C_{fig})(1)(10^{-3}) Pa

Design wind pressure, p = 0.925 C_{fig} kPa

P is added to the cantilevered structure model as triangular loading as per Appendix D5 of MS 1553: 2002.

This value is then calculated in Staad Pro to find maximum reaction at the connection and members sizing adequacy.

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Research Methodology – Back Analysis

Design of Ultimate Anchorage Bond Stress

According to the compulsory British code BS8110, the design ultimate anchorage bond stress must be more than the design anchorage bond stress. The design ultimate anchorage bond stress for bars with a minimum cover of at least one bar diameter and a minimum clear spacing also at least one bar diameter, is equal to:

Design ultimate anchorage bond stress, $\mathbf{f_{bd} = k\sqrt{f_{cu}}}$……………………………**(5)**

where k is a constant depending on the type of bar and whether the bar is in tension or compression and fcu is the cube strength of the concrete. The design anchorage bond stress is:

Design anchorage bond stress, $\mathbf{f_b = T/ (n \times \mu \times d \times L)}$ ………………………..**(6)**

where n is equal to the number of reinforcements on the tension side, d being the diameter of the reinforcement and L is the anchorage length.

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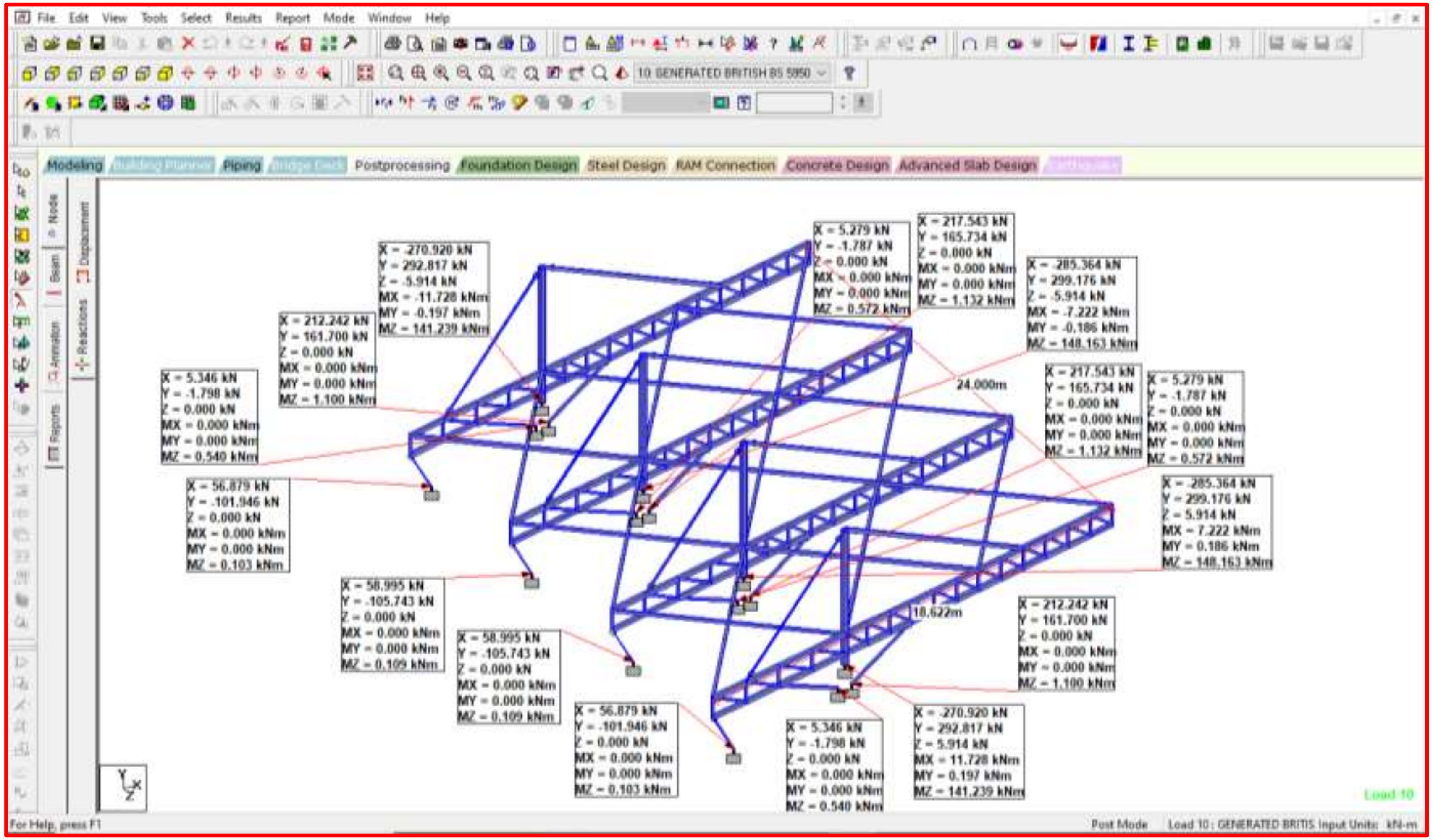
Results and Discussion



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RESEARCH METHODOLOGY

– RESULTS AND DISCUSSION

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Cantilevered Trusses Failure Assessment

Research Methodology – Results and Discussion

- According to Equation 1 and taking the value of k as 0.4 from Table 3.26 of BS8110-1 (Table 3), we obtained the design ultimate bond stress to be:

$$f_{bd} = 0.4\sqrt{35}$$

Design ultimate bond stress, $f_{bd} = 2.366\ N/mm^2$

- From the finite element analysis using Staad Pro, maximum axial load (tension) at the joint between the steel column and reinforced concrete column is 299 kN with maximum moment of 148 kNm and maximum shear as 286 kN. From Equation 6 we obtained the design anchorage bond stress to be:

$$f_b = (299 \times 10^3) / (2 \times \pi \times 20 \times 400)$$

Design anchorage bond stress, $f_b = 5.948\ N/mm^2$

Design anchorage bond stress > Design ultimate bond stress

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Results & Discussion

Although findings at site shows construction differs from as-built drawings, design check proofs members sizing were adequate to support the design load. However, for the steel to concrete connection design, the design anchorage bond stress for the joint was larger than the design ultimate bond stress. Thus, the anchorage bond along the embedded length of the reinforcement bar was inadequate in resisting the tensile force created by the combination of loads.

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Conclusion

Cantilevered Trusses Failure Assessment

Conclusion

It is important for the supervision team to not accept changes to the trusses design without double checking with structural independent checker (certified with Board of Engineers) especially for design and built project (appointment of civil and structural consultant by the contractor) if the supervision officer are unable to check the new design himself.

The reinforced concrete columns were constructed not according to the construction drawings provided, having almost no links on the top section of the column. The consultant supervision team need to closely monitor installation of reinforcement bar before any concreting work is done.

Materials used during construction were also not as per construction drawings. For example, bend deformed bars were used as anchorage when the construction drawing specified holding down bolts to anchor the steel column to the concrete column.