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Structural Forensic Engineering Case Study : MRR2 Project

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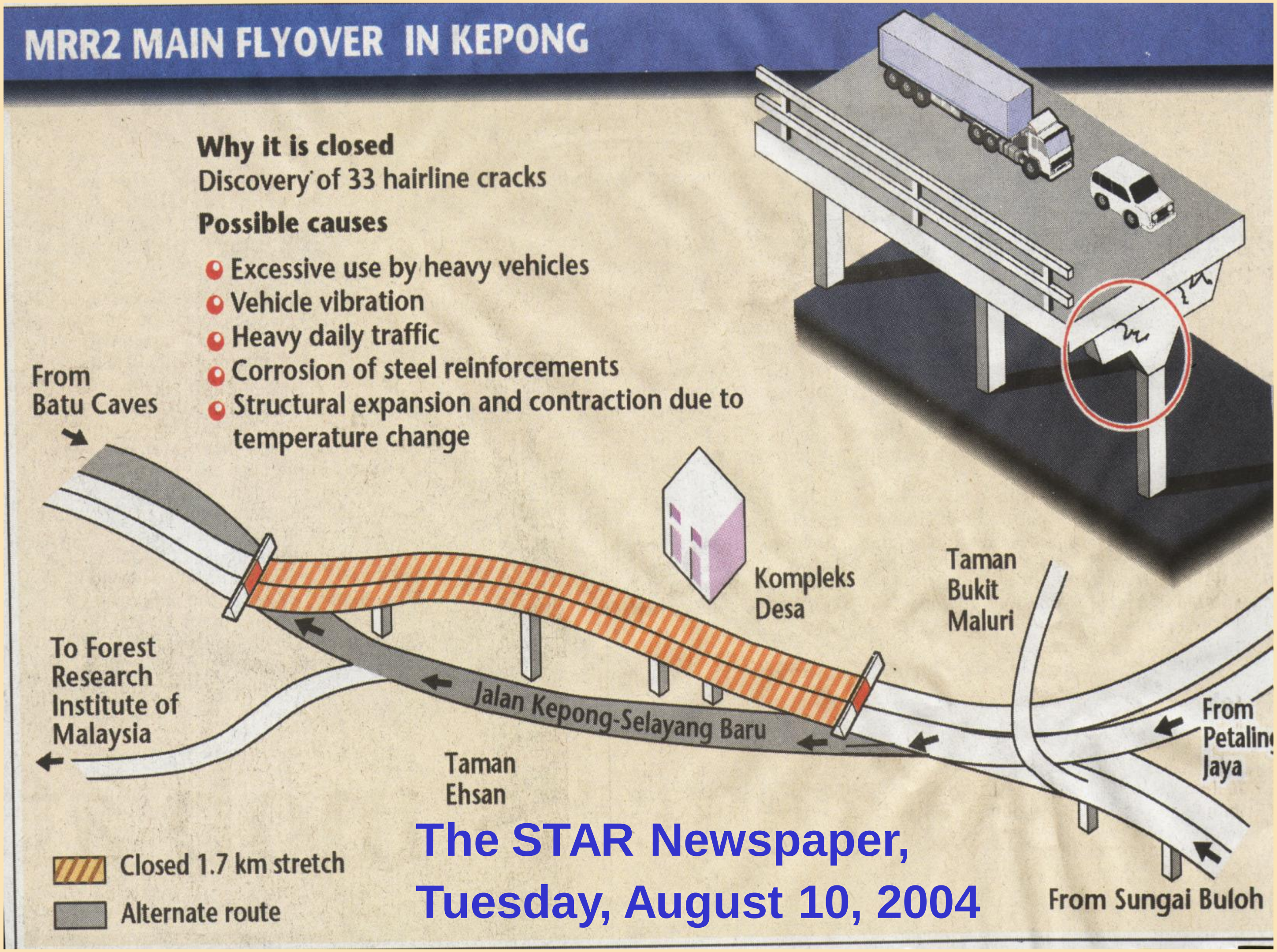
Background



The STAR Newspaper, Tuesday, August 10, 2004

The Observed Cracks

MENDING THE GAPS: Workers inspecting the tiers under the closed Middle Ring Road Two flyover in Kepong, Kuala Lumpur, yesterday. They also carried out grouting work to fill the cracks. The 1.7km flyover between the Taman Bukit Maluri and Forest Research Institute of Malaysia interchanges had been closed to traffic since Sunday because of these cracks. Full report on Page 4. – *STARpix by ART CHEN*

In The News

The Star Online >
Thursday August 26, 2004
ACA to probe technical aspects of MRR2 flyover

SHAH ALAM: The Anti-Corruption Agency (ACA), apart from investigating possible fraud in the construction of the 1.7km flyover along the Middle Ring Road 2 (MRR2), will check whether it was built according to specifications. The ACA, which obtained documents relating to the building of Package 11 of the MRR2, which cost RM238.8mil, from the Public Works Department two weeks ago, is now focusing on the technical aspects of the flyover to check for any discrepancies in its construction.

An eight-man team from the ACA's Engineering Forensic Unit took samples from the damaged pillars and beams and sent them for composition and durability analysis on Tuesday.

An ACA source said the analysis would show whether the concrete chunks were mixed and laid out according to the road construction industry's specifications.

"The investigations will focus on whether those involved cut corners to reap higher profits at the expense of safety and durability. The technical team will verify whether the builder had adhered to the specifications outlined in its building plan," he said. The investigation team led by Rosli Ali measured the length, width and depth of the flyover's pillars and beams.

Works Minister Datuk Seri S. Samy Vellu had on Aug 9 ordered the flyover to be closed to traffic after experts found it to be a threat to public safety. He said it would cost RM20mil to repair the flyover located between Taman Bukit Maluri and the Forest Research Institute of Malaysia.

‘Cracks due to Design’ – Works Minister on MRR2 Flyover

Yesterday (March, 17, 2006), Works Minister Samy Vellu admitted in Parliament that defective design was one of the reasons for the cracks in the Middle Ring Road 2 (MRR2).

"The steel placement did not follow specifications," Samy said in reply to a question from Speaker Tan Sri Ramli Ngah Talib.

Ramli had interrupted Samy Vellu when the minister was giving a technical explanation for the cracks on the MRR2 highway in reply to questions from Datuk Ismail Sabri Yaakob (BN-Bera) and other MPs.

Samy Vellu said his ministry monitored bridges and flyovers but only the MRR2 was found to have "serious defects".

Public Accounts Committee

Repairs to MRR2 flyover cost RM70m

THE Public Accounts Committee (PAC) has revealed that repairs to the MRR2 flyover in Kepong cost more than RM70mil, *Utusan Malaysia* reported.

PAC chairman Datuk Shahrir Abdul Samad said the figure was high compared with its construction cost – RM120mil.

He was quoted as saying that this reflected "shoddy design and construction concepts" that were approved by the Government when projects were given to contractors.

"There is no point in spending more and not being able to use it," he said, adding that it was difficult to pinpoint who was responsible for the mistakes in such a project.

"As an example, the MRR2 project has the contractor and concessionaire constantly pointing fingers at each other. The problems were with the design and construction."

OTHER **NEWS & VIEWS**

Compiled by ROYCE CHEAH, BEH YUEN HUI and A. RAMAN

> *Kosmo!* reported that residents in Ipoh claimed to have seen an unidentified flying object (UFO) after similar reports were made by those in Kampung Terap, Kulim and Seberang Jaya.

Taxi driver Mohd Helmi Hashim, 35, said he was in the midst of sending a passenger from Medan Gopeng to Pengkalan Gate when he saw an object streak through the sky at 6.20am on Monday.

»I was shocked to see the object move so quickly«

MOHD HELMI HASHIM, CABBIE

"I was shocked to see the object move so quickly. It must have been moving at around 300kph-500kph," Mohd Helmi said, adding that the object was orange in colour and was so bright that the dawn sky became clear as day.

Another person, Azmi Lazim, 34, from Sungai Siput, claimed that he saw a UFO while he was passing Chepor, about 5km from Chemor, the daily reported.

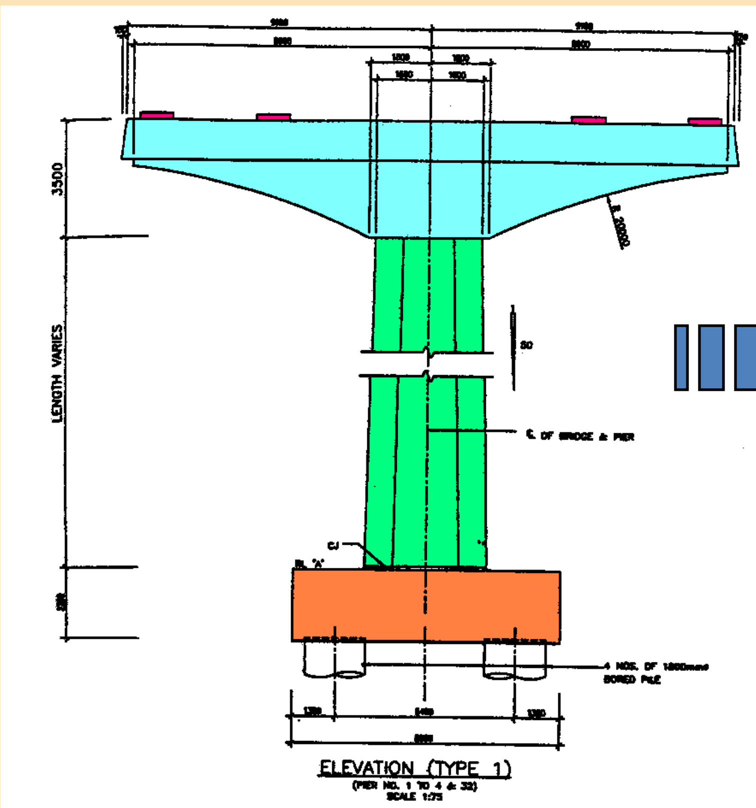
> *Harian Metro* reported that a wayward *bomoh* from the Philippines claimed to be able to make money fall from the sky and conducted his own *akad nikah* (marriage) ceremony with an Indonesian woman recently.

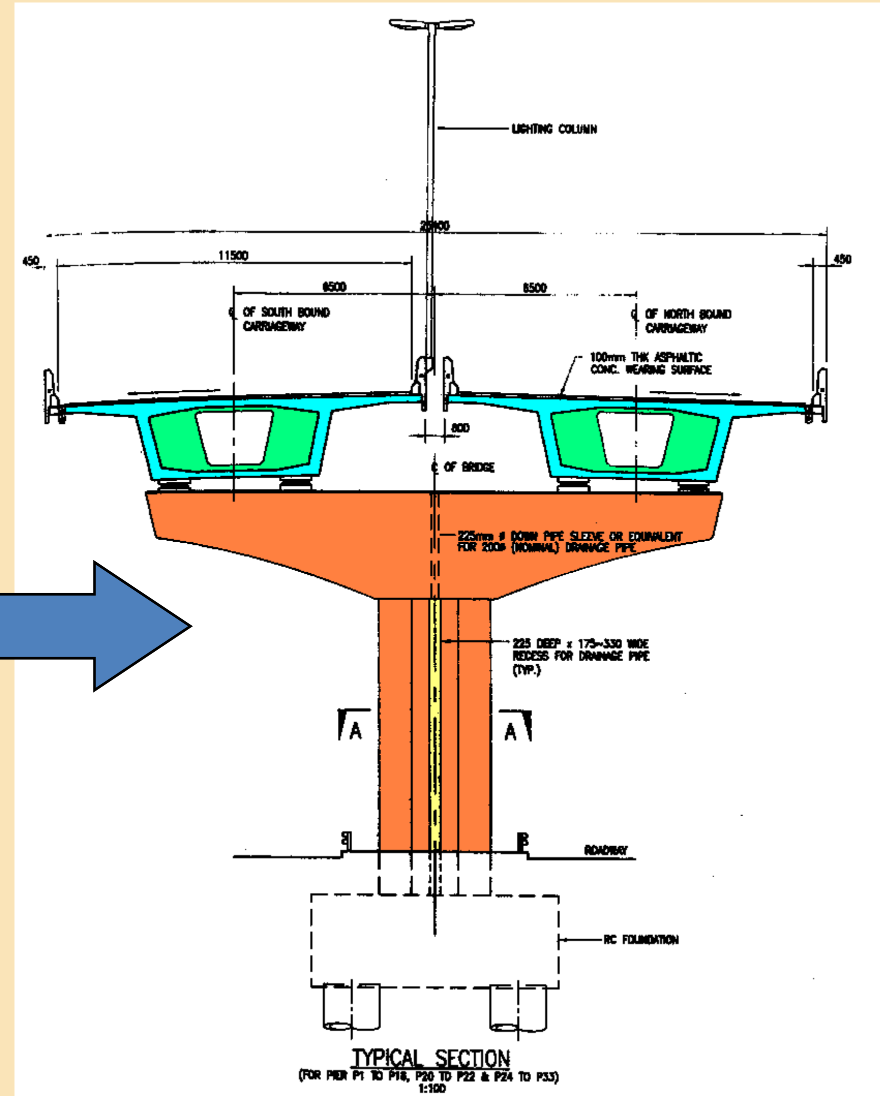
The 45-year-old man is said to have performed *akad nikah* ceremonies for a number of couples in the Old Klang Road area in the past year, where no documents were signed.

A source named Harun said the man would give the excuse that he would get the related documents for the couples in the days following the ceremony but did not do so.

Pier Crosshead

The Bridge Cross-Section





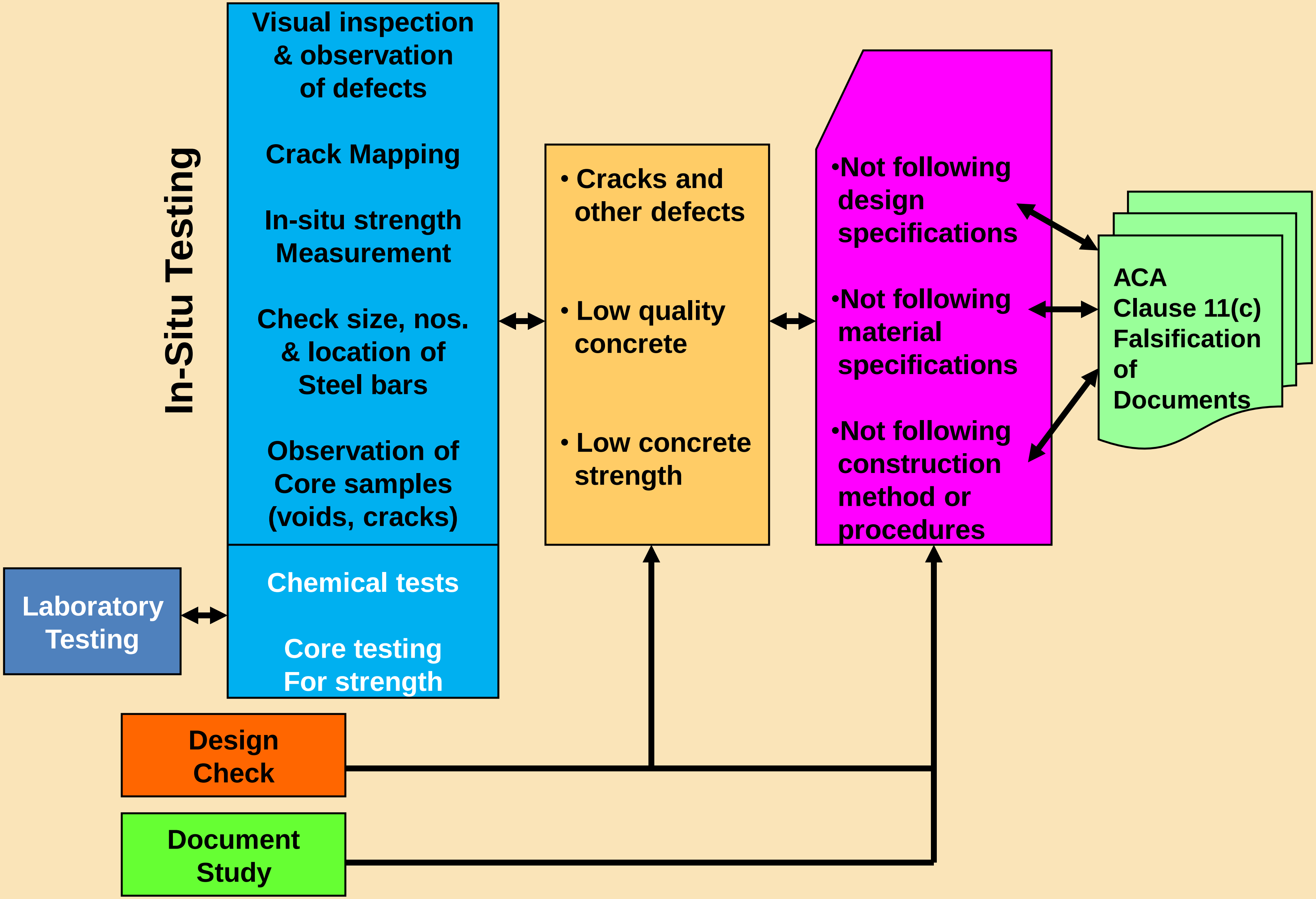
Aim of Forensic Investigation

- Forensics engineering : a ‘failure’ analysis program for litigation support
- The goal is to positively identify the sequence of events leading to ‘failure’
- Common causes of ‘failure’ may be found in deficiencies in design, detailing, material, or workmanship.

Objectives

- Verification of crack mapping and observation of new cracks or defects
- Verification of concrete strength measurement
- Design check on pier crosshead
- Finite element analysis of pier crosshead
- Document study on construction methods and contractual matters

Overview of Methodology



In-Situ Testing

- Visual inspection and selective crack mapping for verification of previous test records and identification of new cracks or defects
- In-situ hardness test using rebound hammer on selected locations to provide estimate of concrete quality and strength correlation
- Core-drilling to extract concrete core samples from selected locations for strength and other relevant tests

Crack Mapping (Verification)

Rebound Hammer Test

Hardness Test Results

Member	Average Rebound Number	Estimated Evaluation of the Concrete Quality
Pier 33 crosshead	55	Sound concrete
Pier 32 crosshead	53	Sound concrete
Pier 30 crosshead	53	Sound concrete
Pier 3 crosshead	56	Sound concrete
Pier 2 crosshead	55	Sound concrete
Pier 32 column	57	Sound concrete
Pier 31 column	56	Sound concrete
Pier 30 column	58	Sound concrete
Abutment A	54	Sound concrete
Abutment B	54	Sound concrete

Covermeter Survey

Core Drilling

- Core-drilling was carried out at 10 selected locations in the abutments and crossheads of selected piers to extract concrete core samples for checking and verifying the material strength.
- The drilling was carried out by skilled operators using a portable rotary cutting equipment and uniformity of pressure during drilling was achieved.
- All holes made by coring were filled up by special non-shrink grout to ensure that they were completely filled up and having smooth surface.

In-Situ Core Drilling

Brief Description of Laboratory Testing

MRR2

Structural Forensic Engineering Investigation

Laboratory Work : Core Testing

Laboratory Work : Core Testing

Laboratory Work : Core Testing

Concrete core under a compression machine

Failure mode of core observed after test

Laboratory Tests

- Compression test on core samples for estimated cube strength determination;
- Visual inspection of core samples for voids and cracks;
- Ultrasonic pulse velocity measurement of core samples for concrete quality and strength assessment;
- Chemical test on concrete for cement content.

Core Strength Test Results

Core Sample No.	P3-S6	P3-S7	P2-S8	P2-S9	P31-S1	P31-S2	P33-S3	P33-S4	P33-S5	AB-S10
Member	**Crosshead**	**Crosshead**	**Crosshead**	**Crosshead**	**Crosshead**	**Crosshead**	**Crosshead**	**Crosshead**	**Crosshead**	**Abutment A**
Direction of coring	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal
Height (as received) (mm)	90	100	135	140	160	150	130	150	105	150
Height (before capping) (mm)	85.9	76.86	76.64	76.86	76.35	76.82	76.25	76.85	76.74	76.88
Height (After capping) (mm)	112.16	85.41	85.95	86.02	85.0	85.65	85.56	86.4	86.49	87.6
Diameter (mm)	100	68.6	68.61	68.67	68.7	68.74	68.84	68.7	68.71	68.68
Cross-section area (mm^2)	7854	3696	3697	3704	3707	3711	3722	3707	3708	3705
Weight in air (kg)	2.02	0.75	0.735	0.74	0.725	0.75	0.735	0.75	0.75	0.74
Weight in water (kg)	1.145	0.425	0.41	0.415	0.41	0.43	0.415	0.425	0.425	0.41
Bulk density (kg/m^3)	2309	2308	2262	2277	2302	2344	2297	2308	2308	2242
Ultimate load (kN)	428.0	232.4	184.4	209.8	178.2	243.1	205.0	230.1	209.2	167.3
Measured strength (N/mm^2)	54.5	62.9	49.9	56.6	48.1	65.5	55.1	62.1	56.4	45.2
Estimated cube strength (N/mm^2)	**59.1**	**68.5**	**54.3**	**61.6**	**52.1**	**71.1**	**59.7**	**67.6**	**61.5**	**49.0**
Type of fracture	Vertical crack	Vertical crack	Vertical crack	Vertical crack	Vertical crack	Vertical crack	Vertical crack	Vertical crack	Vertical crack	Vertical crack

Laboratory Work

- All ten core samples tested exhibited concrete strength about 50N/mm^2 (in compliance with specification)
- Pulse velocities measured on the cores were in excess of 5 km/sec (excellent quality of concrete)

Brief Description of Design Check

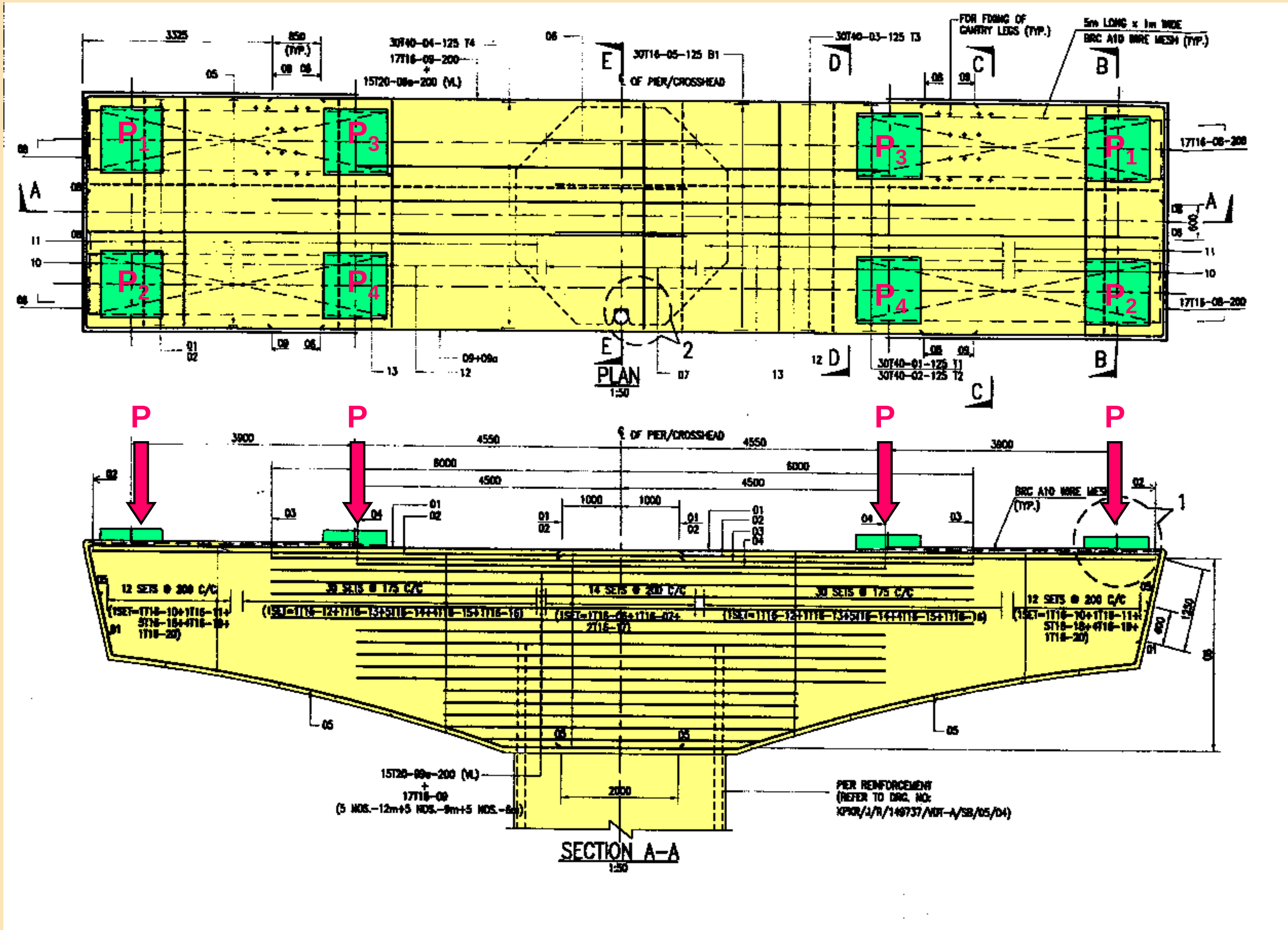
MRR2

Structural Forensic Engineering Investigation

Scope of Design Check

- Design check on pier crosshead for transverse and longitudinal directions (bending; bonding failure; splitting)
- Design check on pier stem;
- Finite Element Analysis for transverse tension on crosshead;
- Finite Element Analysis for assessing the bonding failure effect;
- Finite Element Analysis for assessing shear and deflection of pier.

Design Check

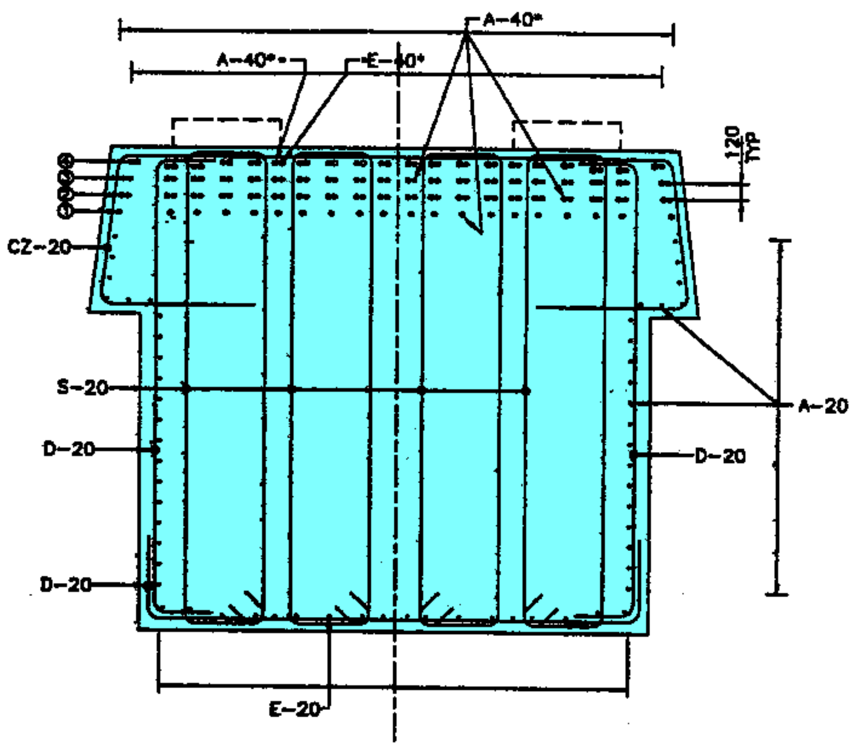


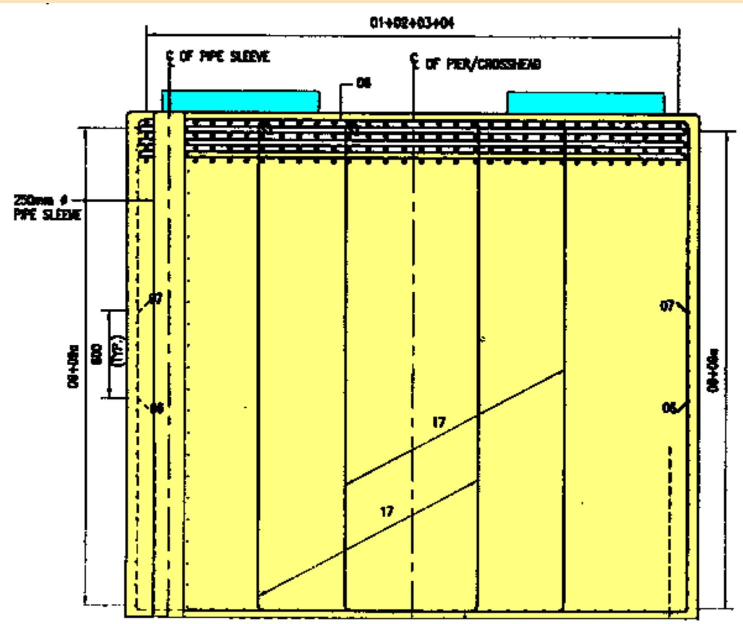
Loading in Design Check

Load Cases	P_1 (KN)	P_2 (KN)	P_3 (KN)	P_4 (KN)
Case 1 : Dead load only	2882	2882	2882	2882
Case2 : Dead load + HA loading	4000	4000	4000	4000
Case 3 : Dead load + (HB45 + HA loading)	4629	4703	2547	2533
Case 4 : Dead Load (SW only) + Erection	5989	2240	2204	2240

Loading After Splitting				
Case 1 : Dead load only	2882	0	2882	0
Case2 : Dead load + HA loading	4000	0	4000	0
Case 3 : Dead load + (HB45 + HA loading)	0	4703	0	2533

Alternative Design Section
- Transverse Steel in Crosshead





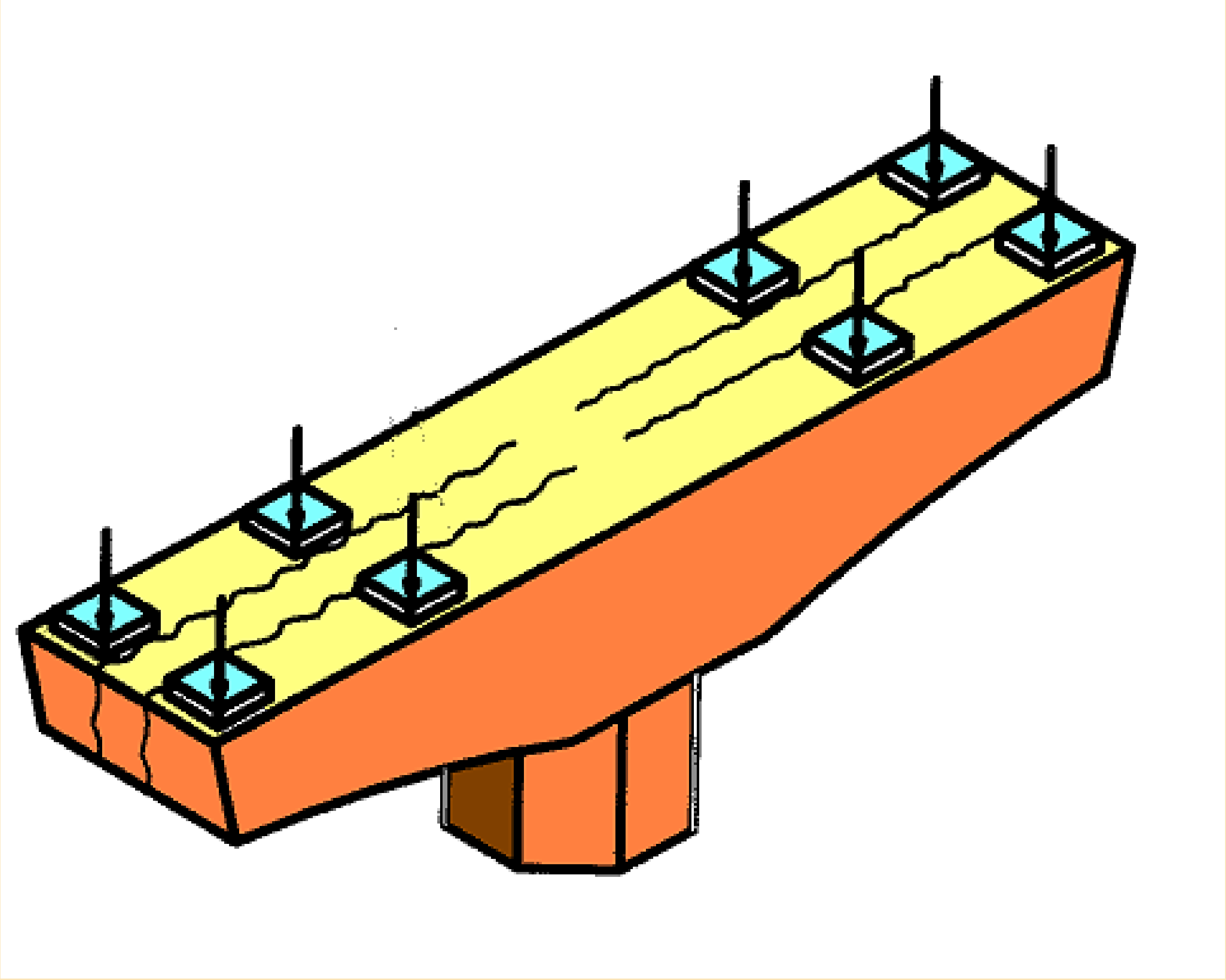
Original Design T20@150mm

Alternative Design T16@175mm

Alternative Design – design check results

Load Case		Max. Longitudinal Moment Mx (kNm)	Reinforcement	Moment Capacity (kNm)	Factor of Safety
1	Selfweight only	8090	128T40	206058	25.47
2	Dead load only	68270			3.02
3	Dead load + HA load	91607			2.25
4	Dead load + (HB45 + HA load)	91615			2.25
5	Erection	81624			2.52
Load Case		**Max. Shear Force Vx (kNm)**	**Reinforcement**	**Shear Capacity (kN)**	**Factor of Safety**
1	Selfweight only	2212	T16-175	30990	14.01
2	Dead load only	13741			2.26
3	Dead load + HA load	18212			1.70
4	Dead load + (HB45 + HA load)	16625			1.86
5	Erection	14885			2.08
Load Case		**Max. Transverse Tension Force Fy (kN/m)**	**Reinforcement**	**Tension Capacity (kN/m)**	**Factor of Safety**
1	Selfweight only	-	T16-175	527	-
2	Dead load only	534			0.99
3	Dead load + HA load	690			0.76
4	Dead load + (HB45 + HA load)	606			0.87
5	Erection	936			0.56

Splitting due to Transverse Tension



Bonding Failure

Load Case	Max. Longitudinal Moment Mx (kNm)	Reinforcement	Moment Capacity (kNm)	Factor of Safety
1 Selfweight only	8090	64T40	106955	13.22
2 Dead load only	68270			1.57
3 Dead load + HA load	91607			1.17
4 Dead load + (HB45 + HA load)	91615			1.17
5 Erection	81624			1.31
Load Case	**Max. Shear Force Vx (kNm)**	**Reinforcement**	**Shear Capacity (kN)**	**Factor of Safety**
1 Selfweight only	2212	T16-175	28052	12.68
2 Dead load only	13741			2.04
3 Dead load + HA load	18212			1.54
4 Dead load + (HB45 + HA load)	16625			1.69
5 Erection	14885			1.88

Splitting due to Transverse Tension

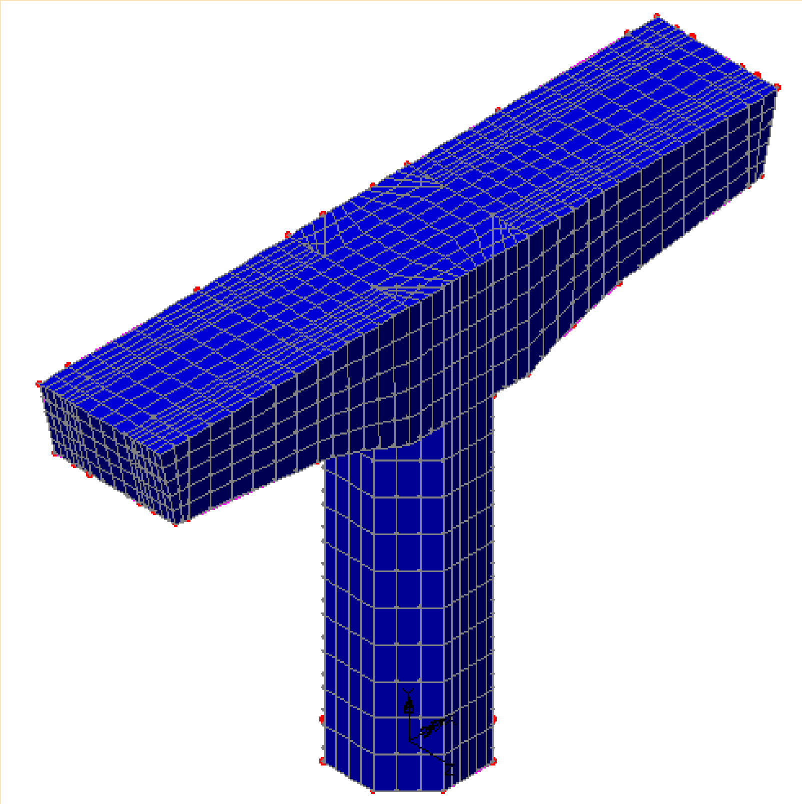
Load Case	Max. Longitudinal Moment Mx (kNm)	Reinforcement	Moment Capacity (kNm)	Factor of Safety
1 Selfweight only	2697	44T40	70558	26.16
2 Dead load only	32787			2.15
3 Dead load + HA load	44455			1.59
4 Dead load + (HB45 + HA load)	44216			1.60
5 Erection	52845			1.34
Load Case	**Max. Shear Force Vx (kNm)**	**Reinforcement**	**Shear Capacity (kN)**	**Factor of Safety**
1 Selfweight only	737	T16-175	10967	14.88
2 Dead load only	6502			1.69
3 Dead load + HA load	8737			1.26
4 Dead load + (HB45 + HA load)	7914			1.39
5 Erection	8930			3.47

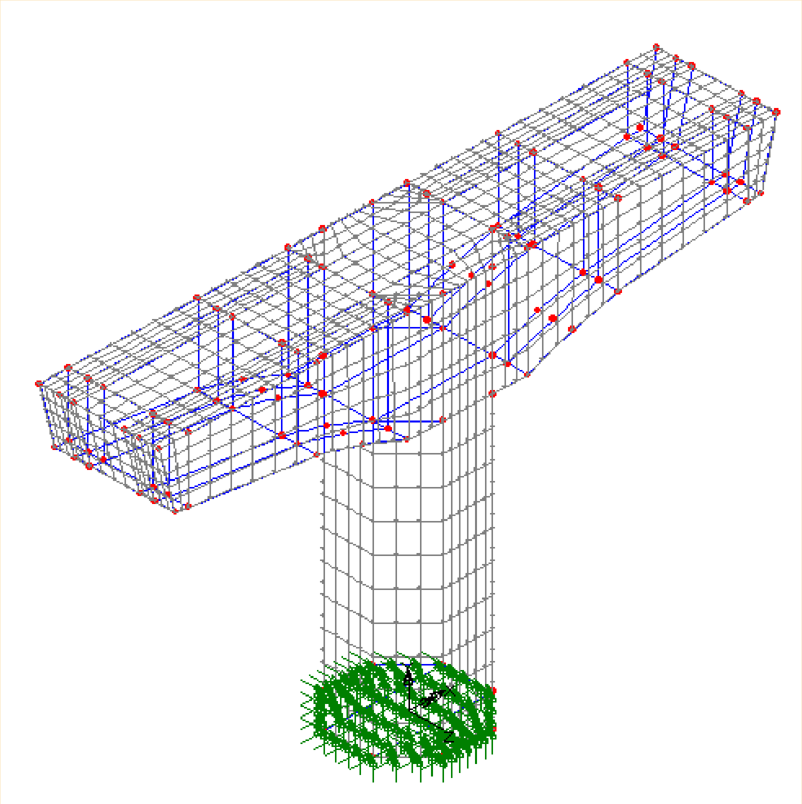
Bonding Failure & Splitting

Load Case		Max. Longitudinal Moment Mx (kNm)	Reinforcement	Moment Capacity (kNm)	Factor of Safety
1	Selfweight only	2697	22T40	37669	13.97
2	Dead load only	32787			1.15
3	Dead load + HA load	44455			0.85
4	Dead load + (HB45 + HA load)	44216			0.85
5	Erection	52845			0.71

Load Case		Max. Shear Force Vx (kNm)	Reinforcement	Shear Capacity (kN)	Factor of Safety
1	Selfweight only	737	T16-175	10188	13.82
2	Dead load only	6502			1.57
3	Dead load + HA load	8737			1.17
4	Dead load + (HB45 + HA load)	7914			1.29
5	Erection	8930			1.14

Finite Element Modeling





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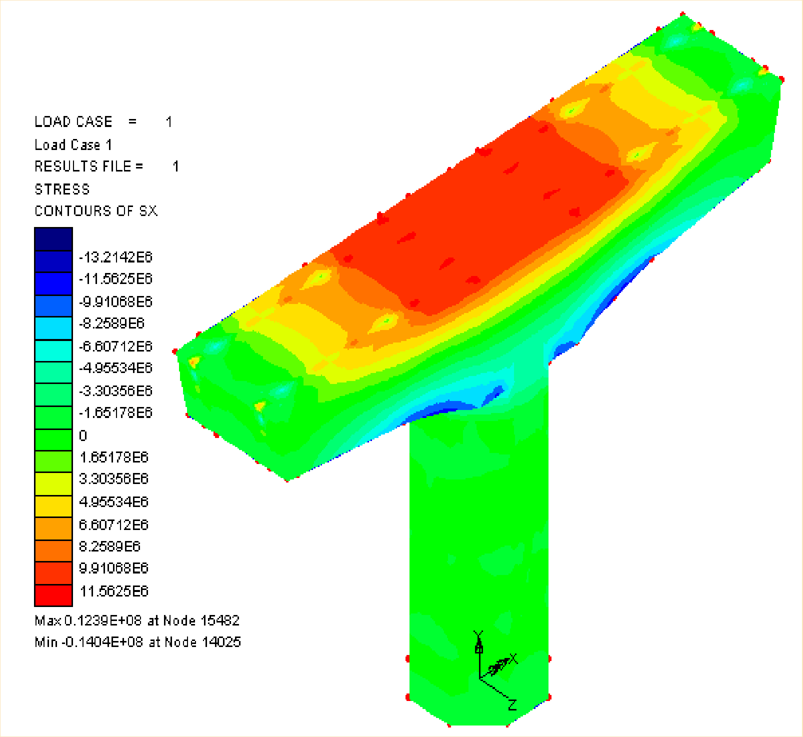
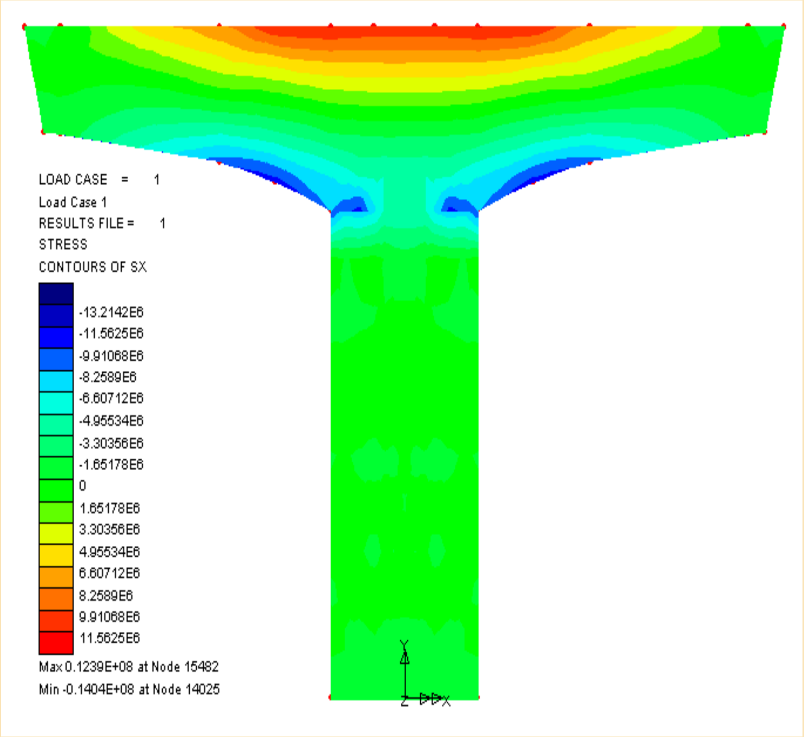
Longitudinal Stresses

3D-View

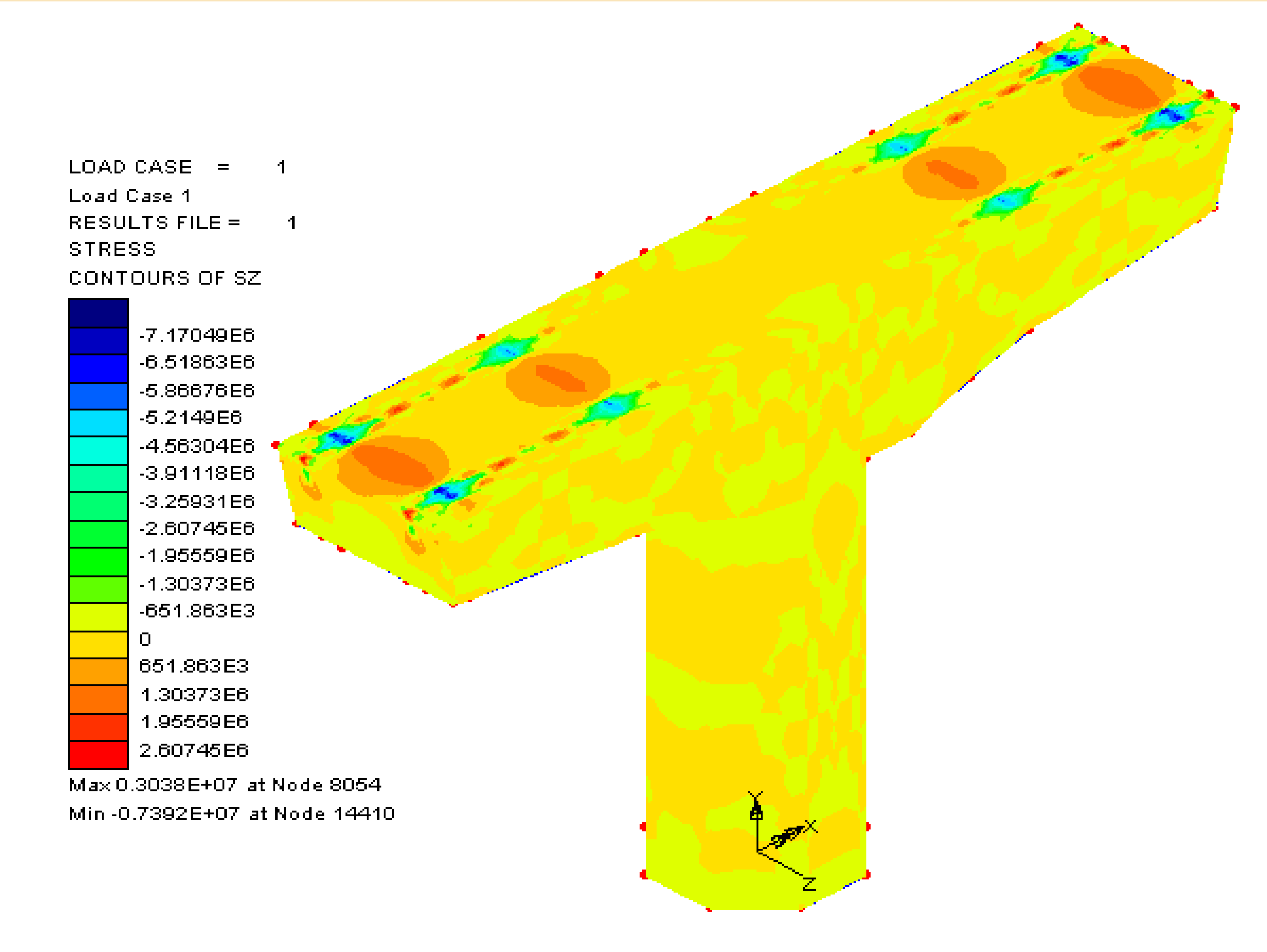


Front View

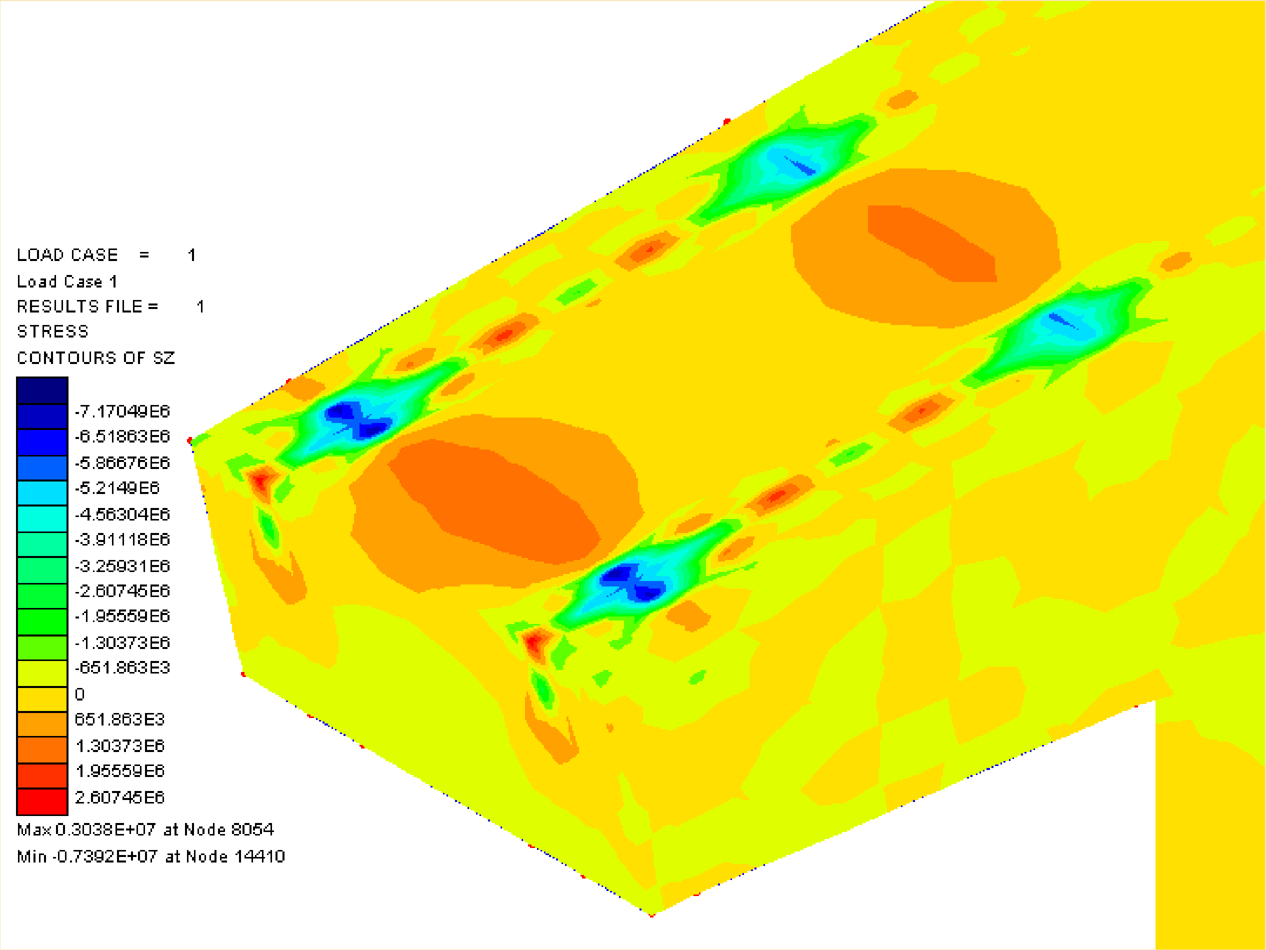


Number of longitudinal bars are adequate. Design is OK for longitudinal direction.

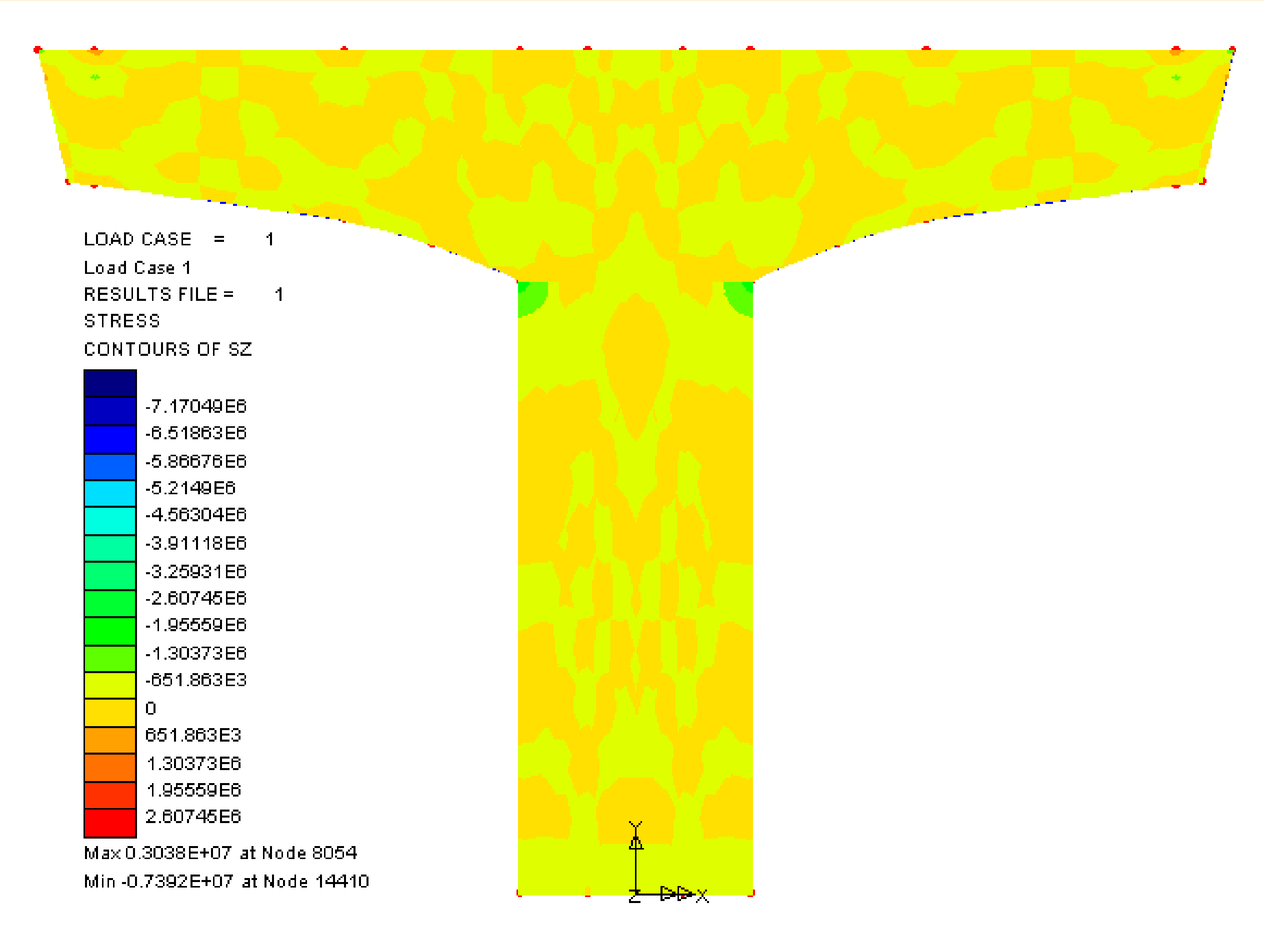
Transverse Stresses – 3D View



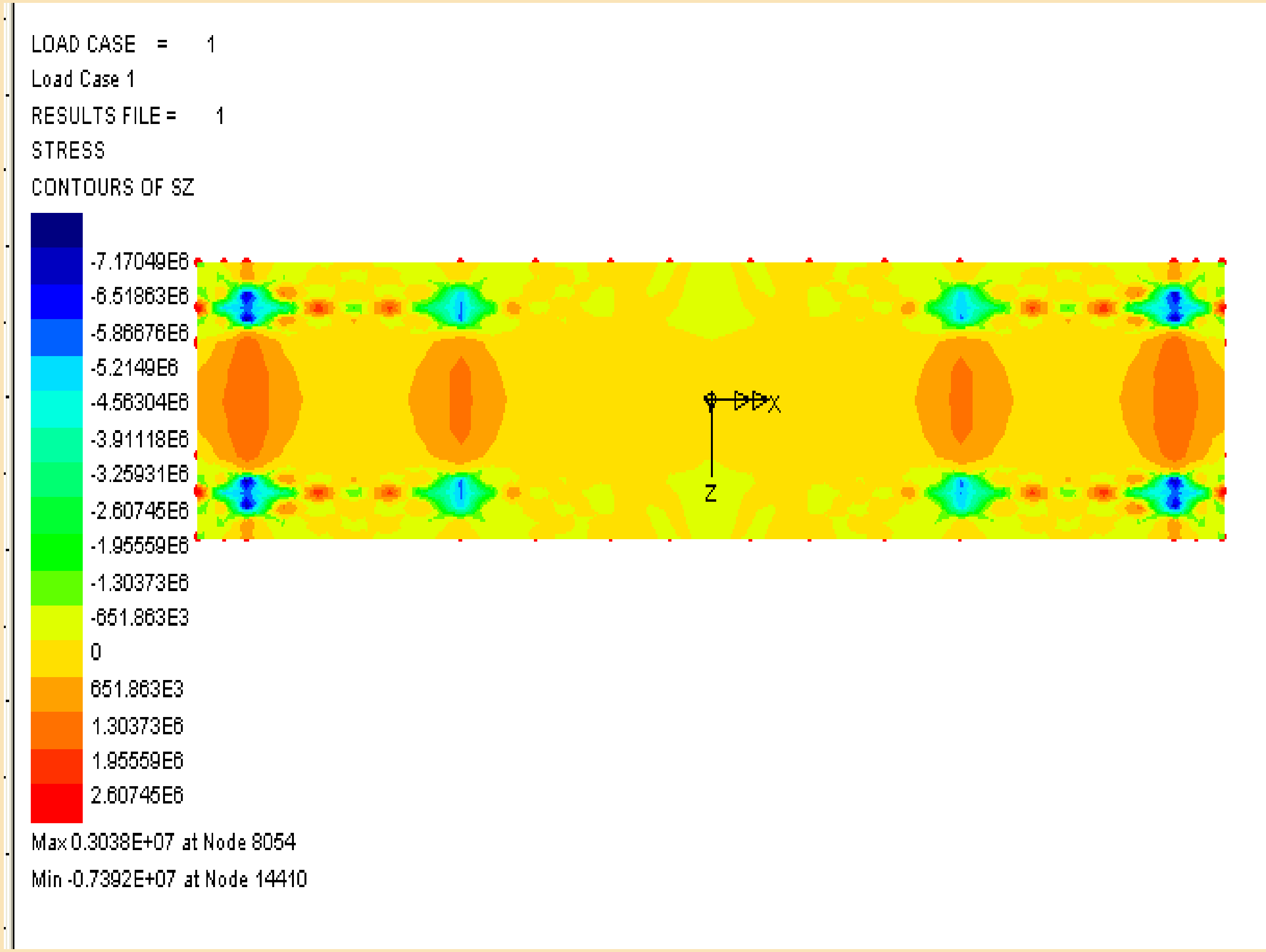
Transverse Stresses (Zoomed at Critical Section)



Transverse Stresses – Front View



Transverse Stresses Plan View



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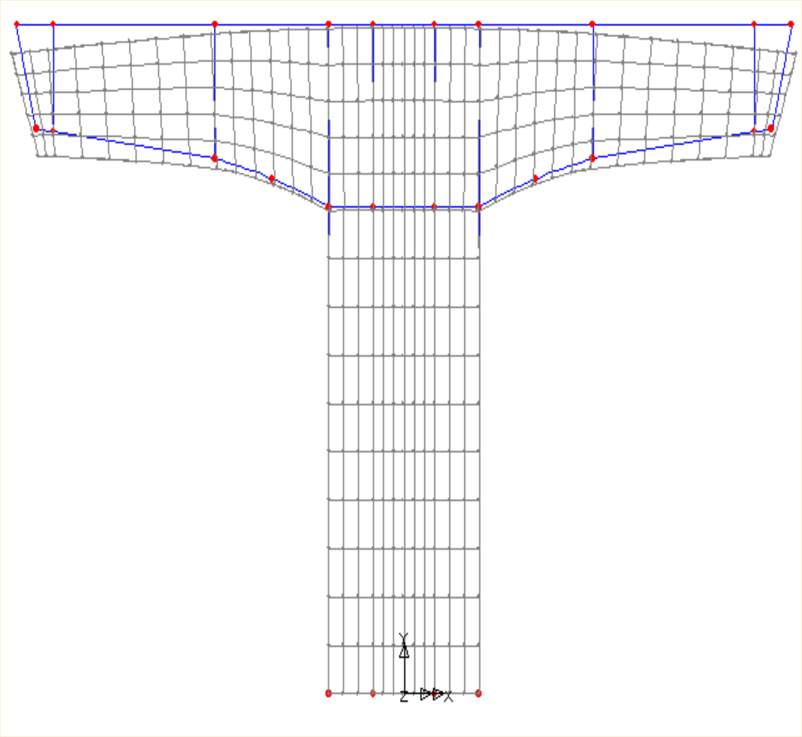
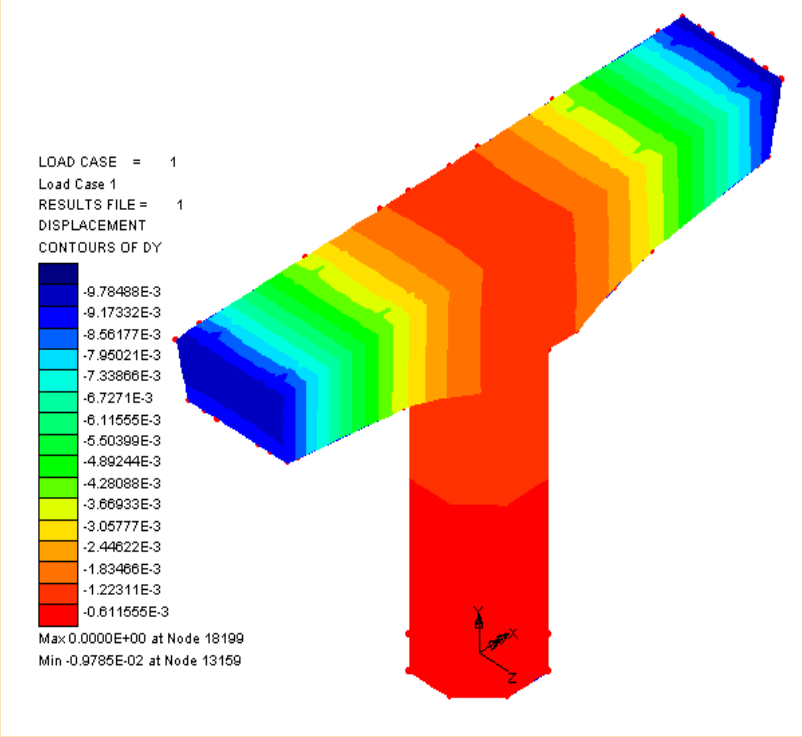
Results of FEM Analysis for Transverse Direction

Load Cases	Tensile Force in Transverse Direction (FEM)	T16@175 mm (Alternative Design MSZ)		T20@150 mm (Original Design ZAR)	
		Allowable Tensile Stress	Remarks	Allowable Tensile Stress	Remarks
Dead Load	89 KN	87 KN	Just OK	137 KN	OK
Dead Load + Live Load	115 KN	87 KN	**Failed**	137KN	OK
Dead Load + HB + HA	101 KN	87 KN	**Failed**	137 KN	OK
Dead Load (SW only) + Erection load	156 KN	87 KN	**Failed**	137 KN	**Failed**

Deformed Shape of Pier





Deflection check is OK

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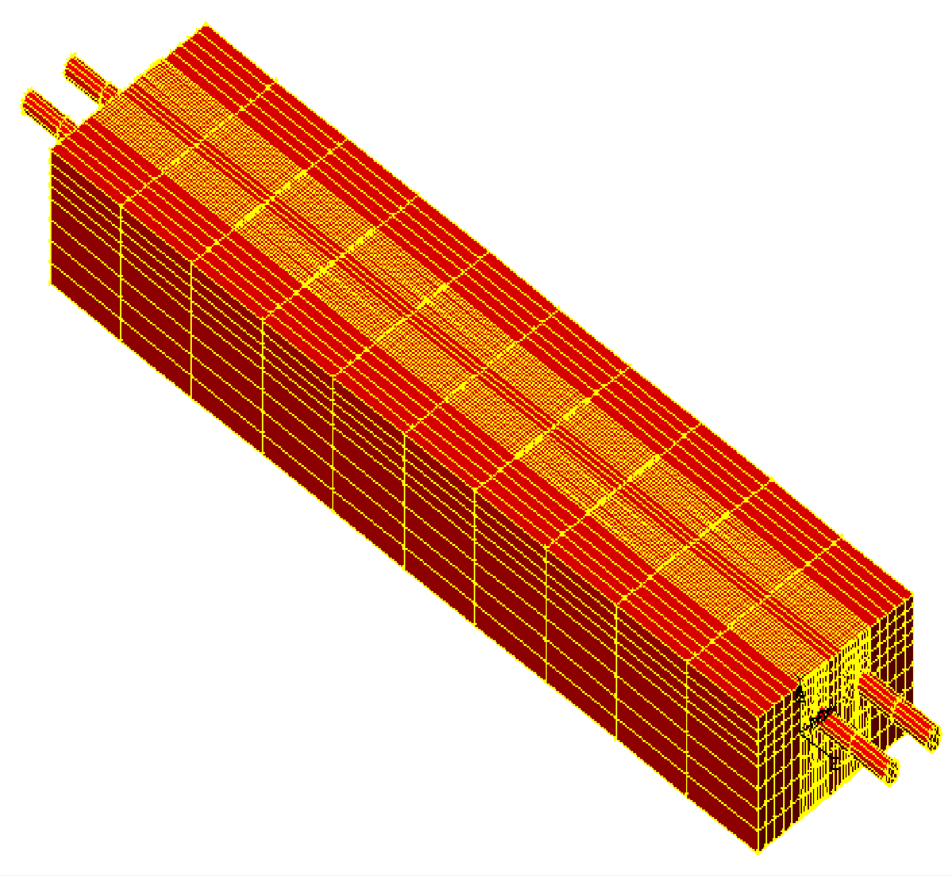
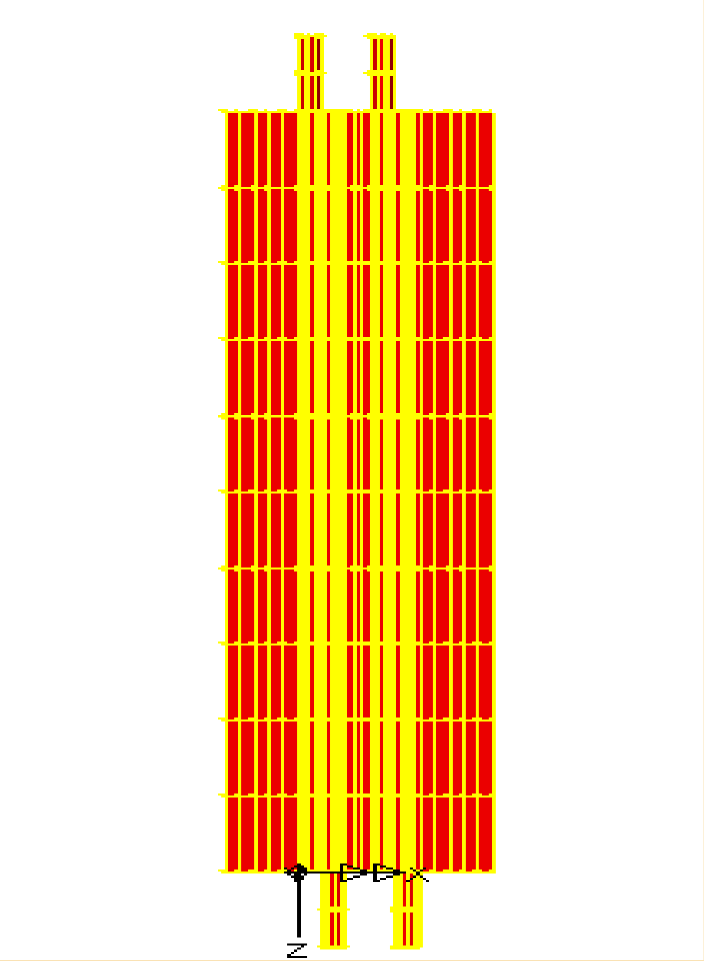
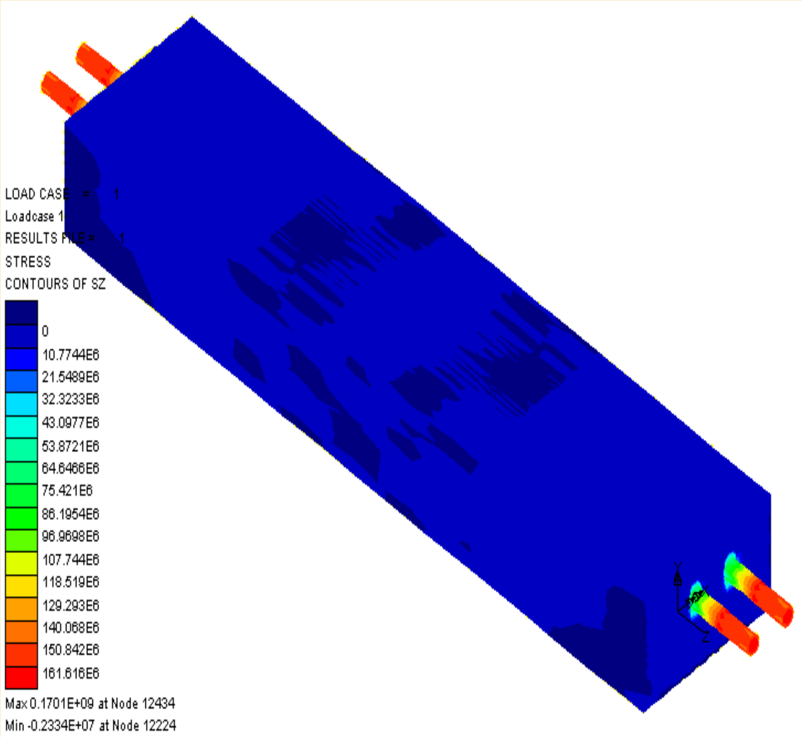
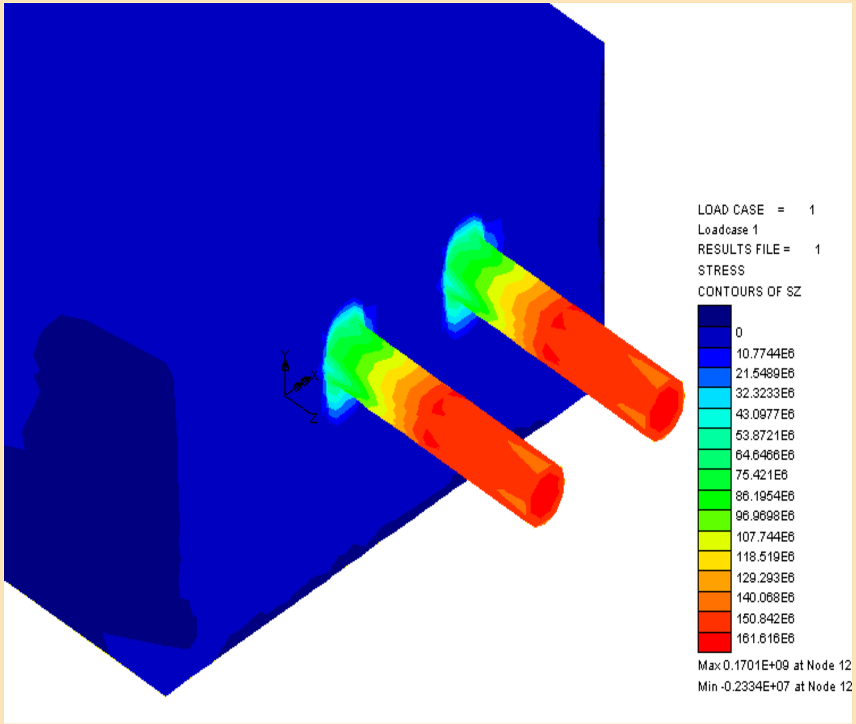
FEM of Bonding (3D view and Plan view)



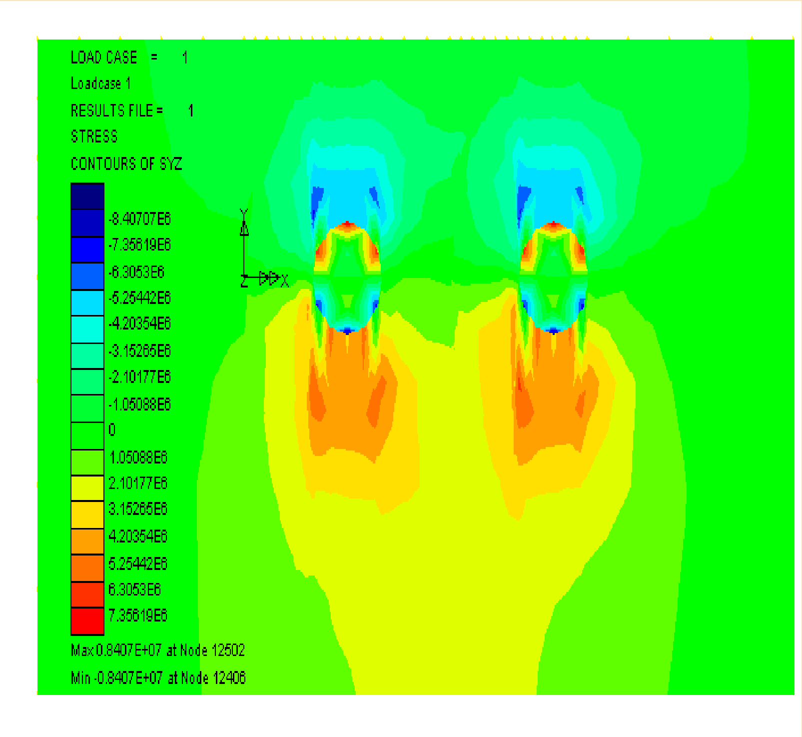


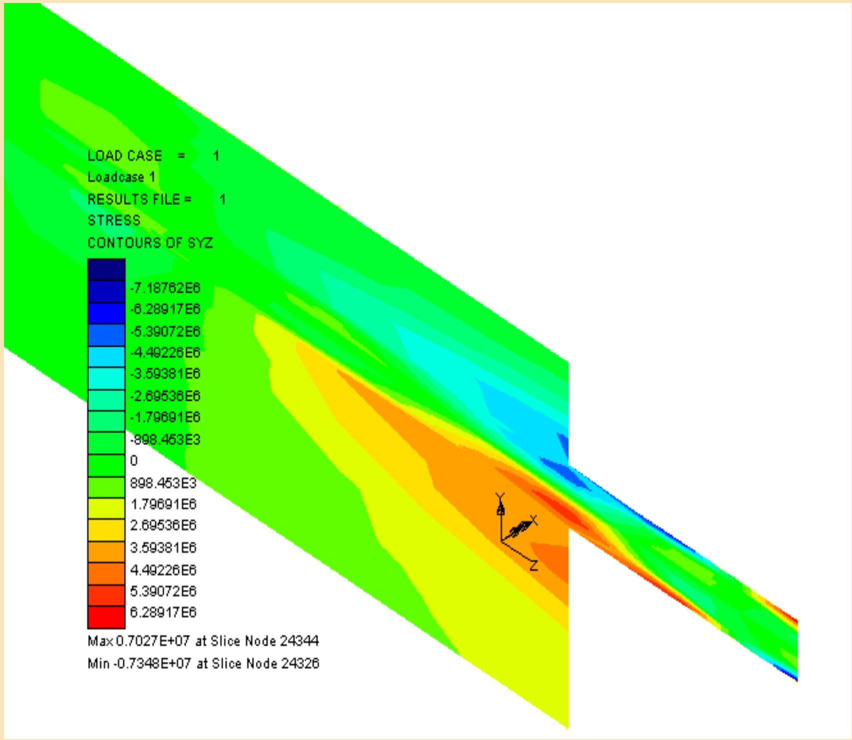
Direct stress contours along longitudinal bars





Shear Stress Contours





Bonding stresses (Front view and along vertical section) ~ 4 to 5 N/mm^2 is greater than the allowable bonding stress of 3 to 3.53 N/mm^2

Brief Description of Document Study

MRR2

Structural Forensic Engineering Investigation

Document Study

Categorization of Documents

- Contractual Matters
- Contract Specification
- Design Specification
- Material Testing
- Construction Records

(a) Progress Reports

(b) Post-Construction Records/NCR/Inspection Records

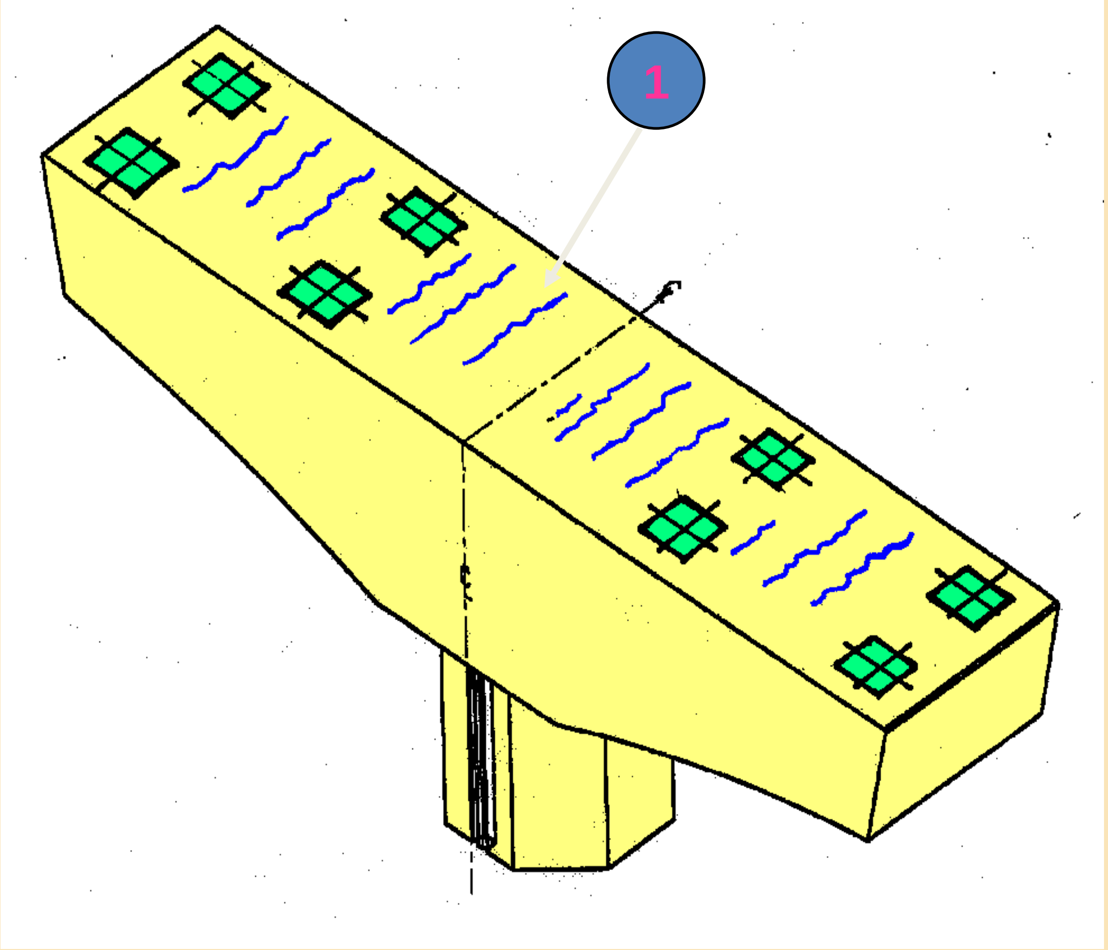
Expected Outcome

- Chronology of construction events & contractual matters;
- Chronology of crack observations and remedial actions;
- Chronology of non-conformance issues (NCR) and corrective actions;

Developing the Failure Hypothesis

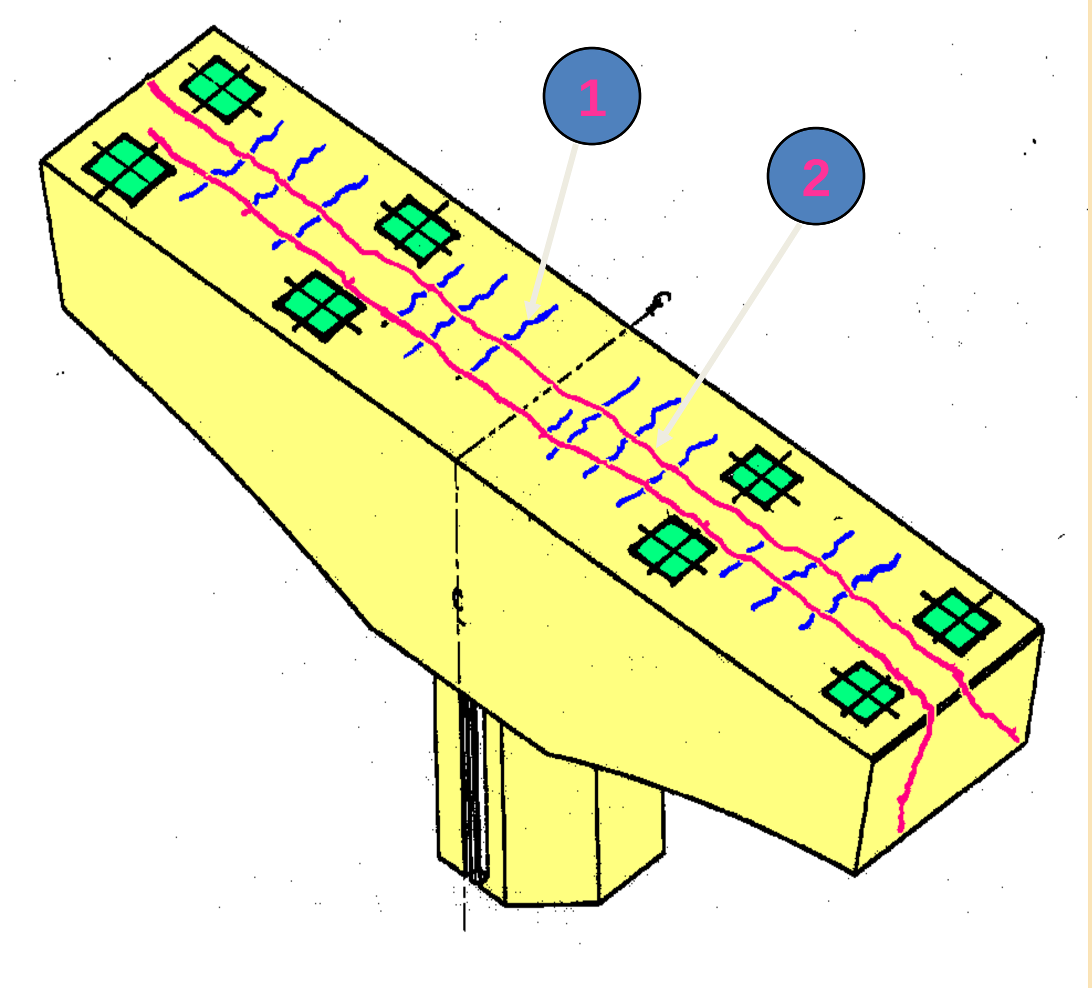
Proposed Chronology of Cracking in Pier Crossheads

Type 1 Cracking



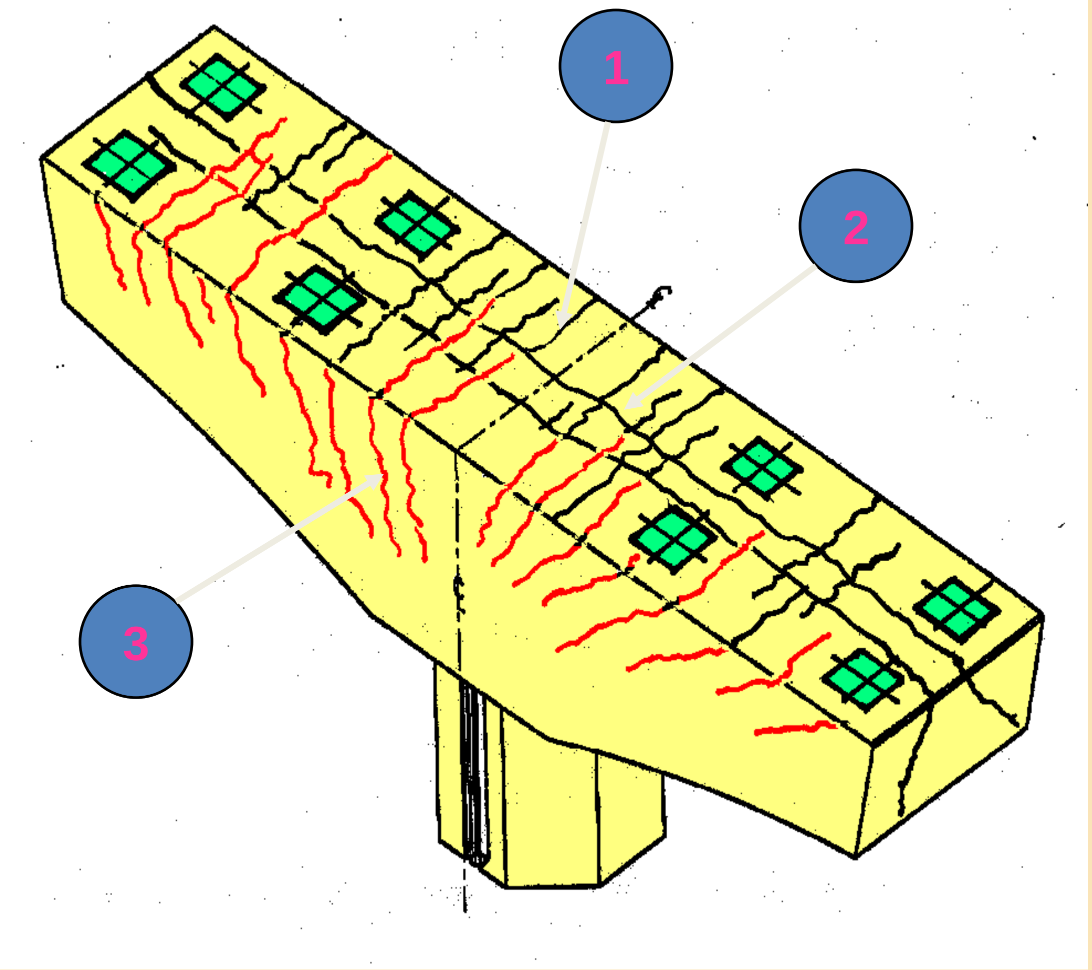
- Non-structural cracks due to early thermal expansion
- Occurred after striking of formwork
- Dead load due to self-weight only
- Insufficient curing and hence cracking is possible if the formwork was struck too early – no evidence to ascertain this

Type 2 Cracking



- Structural cracks – splitting of concrete.
- Inadequate transverse steel to take up tension.
- Cannot take up dead load (SW) plus crane during erection.
- No design calculations for transverse tensile force consideration.
- Factor of safety based on transverse tension is less than 1.

Type 3 Cracking



- Structural bending cracks due to reduced effective width and lack of bonding
- Bonding failure due to lack of bonding in lap at the mid-region of crosshead
- Cannot take up dead load plus crane load due to combined effect of bonding and splitting.
- Factor of safety for longitudinal moment is less than 1.

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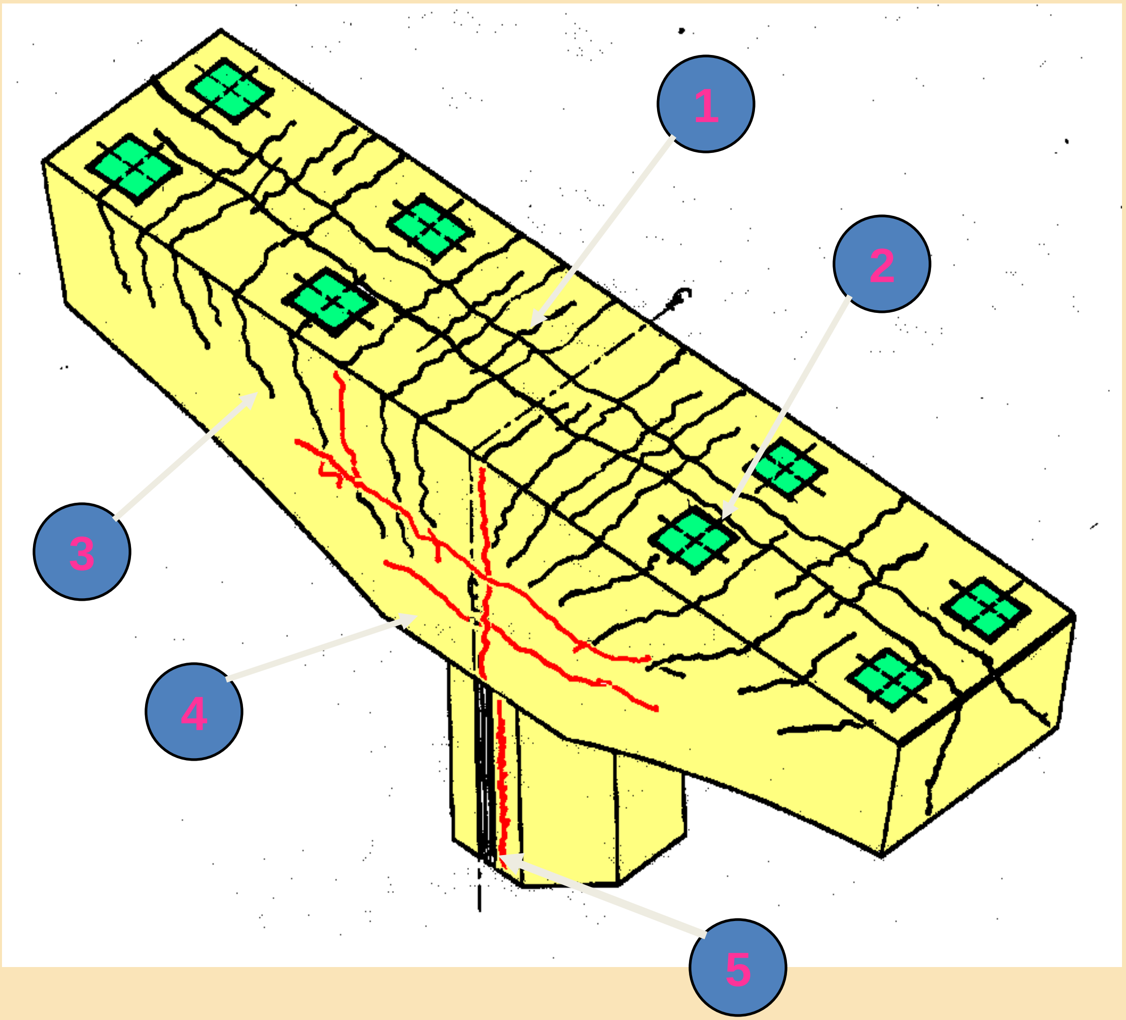
Type 4 & 5 Cracking



- Longitudinal cracks on the face of crosshead.
- New cracks propagated as the steel yielded.
- Vertical crack in pier stem initiated by tensile force at top of stem (see finite element modeling)

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Deficiencies in Design

- Alternative design did not provide adequate transverse steel in the crosshead;
- Alternative design T16@175mm (replaced T20@150mm in the original design) was inadequate in resisting tension in the crosshead.
- This failure to take up transverse tension had caused splitting during erection of the box girders.
- The design calculations should have taken into account all loads including the crane loads during erection.
- The calculations for transverse steel in the alternative design and the consultant's assessment of the cracks were grossly missing.

Deficiencies in Detailing

- Location of lap for longitudinal bars in the mid-region of crosshead was not appropriate as it caused congestion of reinforcement – spacing of about 50mm between bars could not provide sufficient concrete for bonding.
- This had caused bonding failure even when the material quality and strength was adequate.
- Details in original design provided sufficient spacing between longitudinal steel (120mm) and there was no lap in the middle region of crosshead.

Procedural & Contractual

- Procedures to be adhered in the management of a design and build procurement system by both parties were more akin to those in a conventional procurement system, thus ‘best practices’ were not utilized.
- Although contractual matters pertaining to payment are clear and definite, it is against the normal procedures or usual practices in certifying work done. Coupled with the uneven risks distribution, the client’s interest was compromised at all times during the construction period.

Observation of Cracks During & After Construction

Events / Dates	5/99	8/00	11/00	7/01	8/01	3/02	11/02	7/03
Project Commenced	X							
Reported Cracks in Pier 1 & Pier 2		X						
Reported Cracks at Pier 1 to Pier 5			X					
Reported Cracks in Pier 19 Crosshead				X				
Reported Cracks in Pier 20 Crosshead					X			
Viaduct opened to traffic						X		
Reported Cracks in the Crossheads							X	
Reported Cracks in all Piers 1-33, and Abutments A&B								X

Terima Kasih