Flexural Strength and Behavior of Inverted-T Precast Concrete Beam Reinforced with Modified Smooth CFRP Bars

Sunday, March 24, 2024
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Session 10: Behavior and Design of Prestressed Concrete Structures

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Introduction

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Introduction – Research Background

Disintegration

Leakage

Spalling & delamination

Cracks

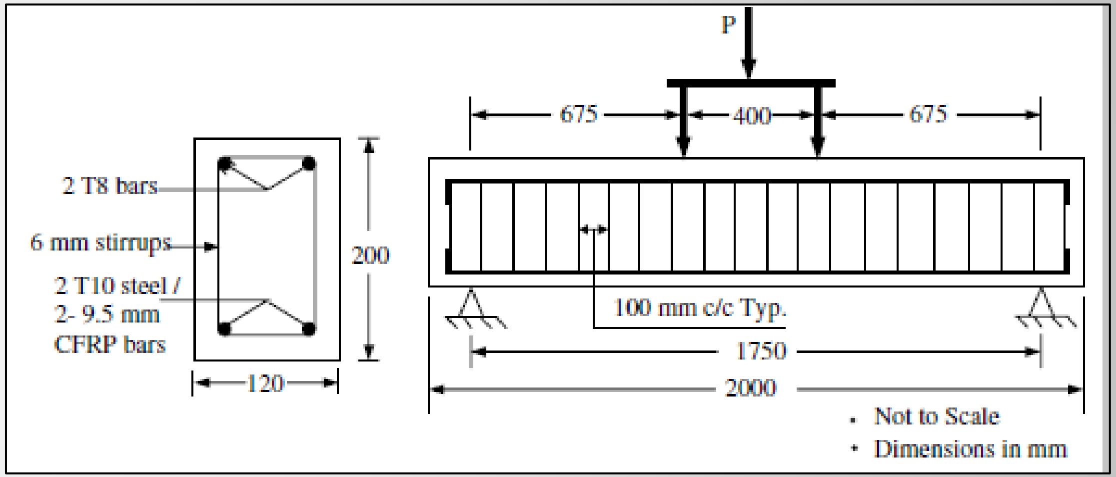
Excessive deflection

Steel reinforcement corrosion leads to serious structural failure

Spalling & delamination

Cracks

Introduction – Research Background



- ❖ Application of carbon fiber reinforced polymer (CFRP) bars as a flexural reinforcement in the RC structures to overcome the corrosion issues.

Introduction – Problem Statement

Various types of deformed and non-deformed CFRP bars are offered in the industries.

Smooth (non-deformed) CFRP bar is not recommended to be applied as flexural reinforcement (poor bond strength with concrete).

Limited research on smooth CFRP bar contribute to the gap of knowledge.

To improve the bond strength on smooth CFRP bar with new technique.

To apply the modified smooth CFRP bars as flexural reinforcement in precast beam

Various types of surface treatment of CFRP bars

Introduction – Research Objectives

MAIN OBJECTIVE: To determine the flexural strength and behavior of precast concrete beam reinforced with modified smooth CFRP bars

SPECIFIC OBJECTIVE 1

To ascertain the bond behavior of modified smooth CFRP bars and concrete

SPECIFIC OBJECTIVE 2

To evaluate the flexural responses of inverted-T precast concrete beam reinforced with modified smooth CFRP bars

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Literature review

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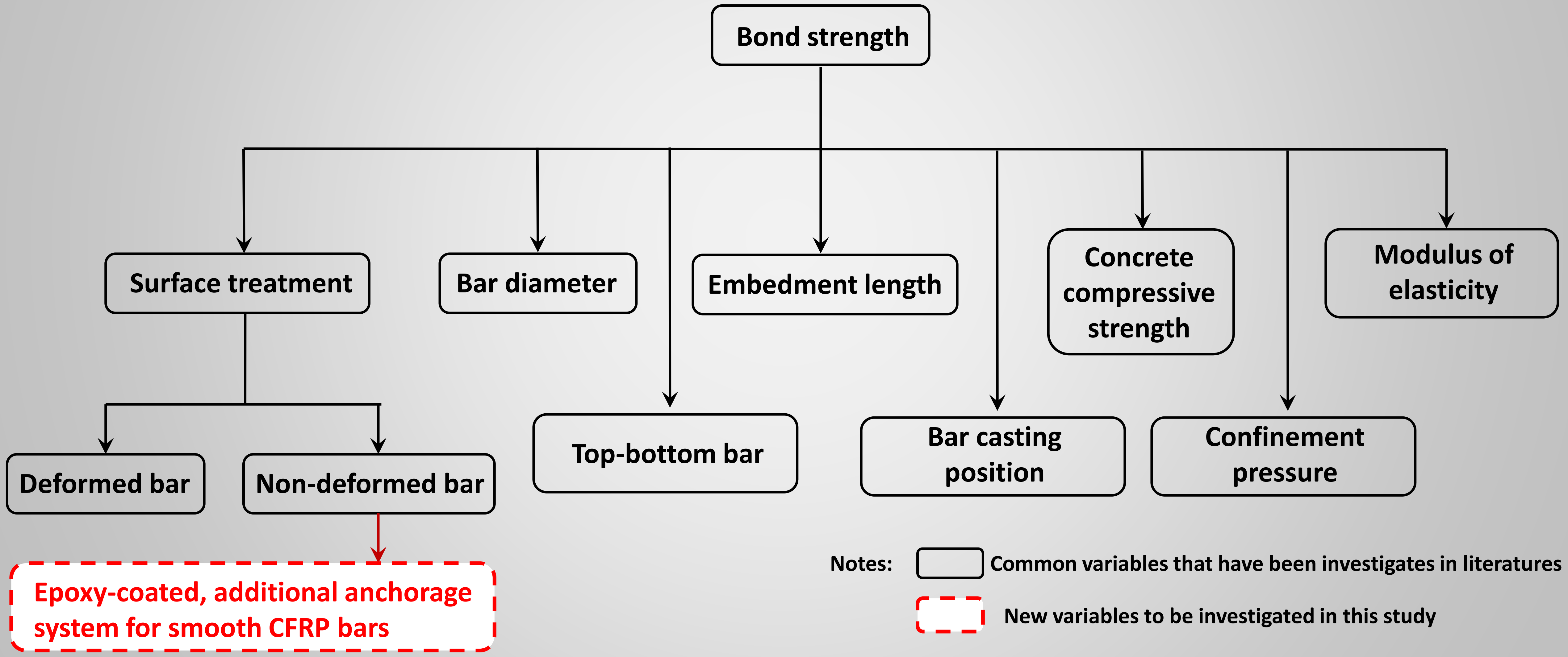
Literature Review – Bond strength

- (Achillides & Pilakoutas, 2004; Benmokrane et al., 2002; Hao et al., 2009; Okelo & Yuan, 2005): concern about insufficient bond behaviors of FRP bars in concrete with relatively lower bond strength than steel bars under similar conditions.
- In general, bonding mechanism of CFRP bars mainly consists of chemical adhesion, friction and mechanical interlocking.
- Bonding mechanism for non-deformed CFRP (smooth) bars, however, only consists of chemical adhesion, frictional resistance. Hence, smooth CFRP bars are not recommended to be utilized as flexural reinforcement unless there are provided with adequate anchoring systems.
- In this study, a new anchorage system together with modified surface treatment is proposed to enhance the bond properties of smooth CFRP bars in concrete.

Factors affecting bond strength of CFRP bar in concrete



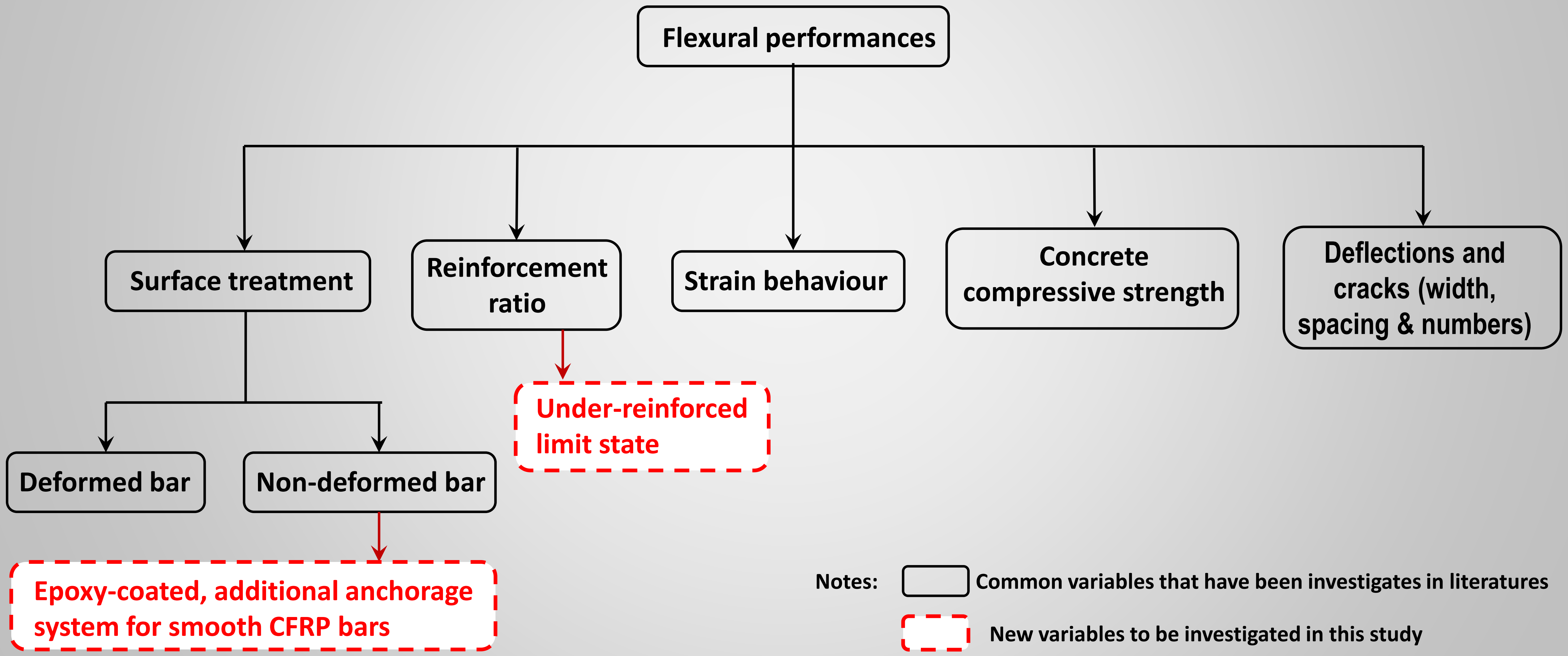
CFRP reinforcement in RC beams

RESEARCHER (S)	VARIABLES	METHOD OF TESTING	FINDINGS
Ashour and Habeeb (2008) Title: Continuous concrete beams reinforced with CFRP bars	Reinforcement ratio	Flexural test with 3 and 4 point loads.	a) Increase CFRP reinforcement ratio at bottom layer: enhance load capacity and controlling deflection; b) **De-bonding of CFRP bars from concrete** was an important issue that needs further investigation.
ZY Sun *et al.* (2012) Title: Experimental study on flexural behavior of concrete beams reinforced by steel-FRP composite bars	Different reinforcement types (FRPs and steel).	Flexural test with 4 point loads	a) Loading process (FRP) divided into 3 stages: elastic stage before cracking, service stage after cracking and stage after the rupture of FRP; b) **Diameter of FRP influences bonding behavior** of FRP bar to concrete.
Lin & Zhang (2013) Title: Bond-slip behaviour of FRP-reinforced concrete beams	Bar types and surface treatment: a) smooth surface of CFRP and GFRP bars; b) spiral wrapped of BFRP bars.	Flexural test with 4 point loads	a) **Poor bonding between the bar with smooth surface and concrete:** CFRP RC beams show large increases in deflection and very low in load bearing capacities; b) **Bond–slip** is proven to exert great influence on flexural behaviour of FRP RC beams; c) **Very poor structural performance and bond condition** are observed on CFRP RC beam with smooth bar surface.

CFRP reinforcement in RC beams

RESEARCHER (S)	VARIABLES	METHOD OF TESTING	FINDINGS
Eugenijus Gudonis *et al.* (2013) Title: FRP reinforcement for concrete structures: state- of-the-art review of application and design	Structural applications using CFRP bars	Paper review	Main attention should be paid to the following factors for designing FRP RC structures: a) Proper selection of FRP material under severe environmental conditions; and, b) **Bond properties** as the governing criteria for deformational analysis.
Suzan A.A. Mustafa *et al.* (2017) Title: Behavior of concrete beams reinforced with hybrid steel and FRP composites	RC beams reinforced with different reinforcement types (FRPs and steel).	Simulation on flexural test using finite element software	a) Replacing steel bars by CFRP bars in RC beam shows 1.32 higher than ultimate capacity of the conventional beams; b) **Higher FRP reinforcement ratio**: Less rate in increasing ultimate moment capacity.
Ahmed *et al.* (2020) Title: Flexural strength and failure of geopolymer concrete beams reinforced with CFRP bars	a) Reinforcement ratio; b) Conrete compressive strength (20, 35 & 50 MPa); c) Concrete types (GPC & OPC)	Flexural test with 4 point loads	a) 4 different types of failure observed: (1) Tension failure, (2) tension–compression failure, (3) compression failure and **(4) debonding failure**; b) Reinforcement ratio: Beam stiffness (beams with low reinforcement ratio recorded significant deformation); c) Compressive strength: Significant effect on the first crack, crack width and deflection;

Factors affecting the aspects of behavior of RC beams reinforced with CFRP bars



Literature Review - Summary

Throughout the literature review, it can be observed that:

a) Bond strength between CFRP bars and concrete:
   1. The poorest bond performance with concrete: smooth CFRP bar;
   2. Smooth CFRP bars are not recommended to be applied in structural applications;
   3. New technique need to be investigated and documented in order to enhance the bond strength.

b) CFRP reinforcement in RC beams
   1. Non-rectangular beams have not been tested in the literatures.
   2. CFRP RC beam experiences 4 different types of failure modes: (1) Tension failure for under-reinforced beam; (2) Tension-compression; (3) Compression failure for over-reinforced beam; (4) De-bond failure of CFRP from concrete.
   3. Researchers were concerning with the de-bond failure of CFRP from concrete as this failure is sudden and catastrophic.
   4. Over-reinforced limit state is more preferable in designing the CFRP RC beams.

In this study, precast concrete beams are designed as under-reinforced limit state. The bond performance of modified smooth CFRP bars are vital to avoid any de-bond failure of CFRP bars with concrete. The tensile strength of CFRP bars will be fully utilized as the precast beams are fail by tension failure.

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Materials and methods

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Materials and methods

STAGE	VARIABLE	METHODS OF TESTING	NUMBERS OF SPECIMEN	CODE OF PRACTICE
Stage 1	Bonding strength between CFRP bars and concrete	Pull-out test using 150 x 150 150 mm cube.	21 specimens	1. ACI 440.3R-12 2. CSA S806-12
Stage 2	Flexural performances of precast concrete reinforced with modified smooth CFRP bars	Flexural test with 4 point loads: Full-scale of 9 sets precast inverted T-shaped beam specimens with size *400 mm x 600 mm x 5000 mm (according to the JKR IBS Catalogue Version 2:2020)	9 beam specimens	ACI 440.1R-15

Pull-out test details

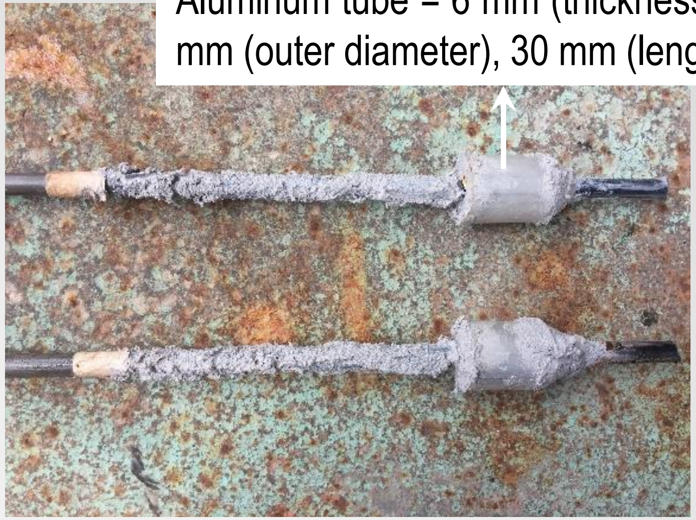
Set*	Notation	Surface Treatment				Concrete Cover (mm)	
		Smooth (S)	1 mm Sikadur-30 Coated (EC)	Deep Embedment (DE)	Additional Anchorage (AA)	50 (Eccentric)	71 (Centric)
1	C1-S-C	✓	X	X	X	X	✓
2	C2-EC-C	X	✓	X	X	X	✓
3	C3-EC-E	X	✓	X	X	✓	X
4	C4-DE-C	X	X	✓	X	X	✓
5	C5-DE-E	X	X	✓	X	✓	X
6	C6-AA-C	X	✓	X	✓	X	✓
7	C7-AA-E	X	✓	X	✓	✓	X

Note: * - Each set encompass of three identical specimens.

Specimen notations: 1) C1 – represents specimen numbering;
2) S – smooth (no treatment) surface;
3) EC – epoxy coated (average of 1 mm thickness);
4) DE – deep embedment;
5) AA – Additional anchorage by using aluminum tube;
6) C – centric position;
7) EC – eccentric position.

Pull-out test

CFRP bars: smooth bar and coated with Sikadur-30 (average of 1 mm thickness)



CFRP bars: coated with Sikadur-30 (average of 1 mm thickness) and additional anchorage

Casting works

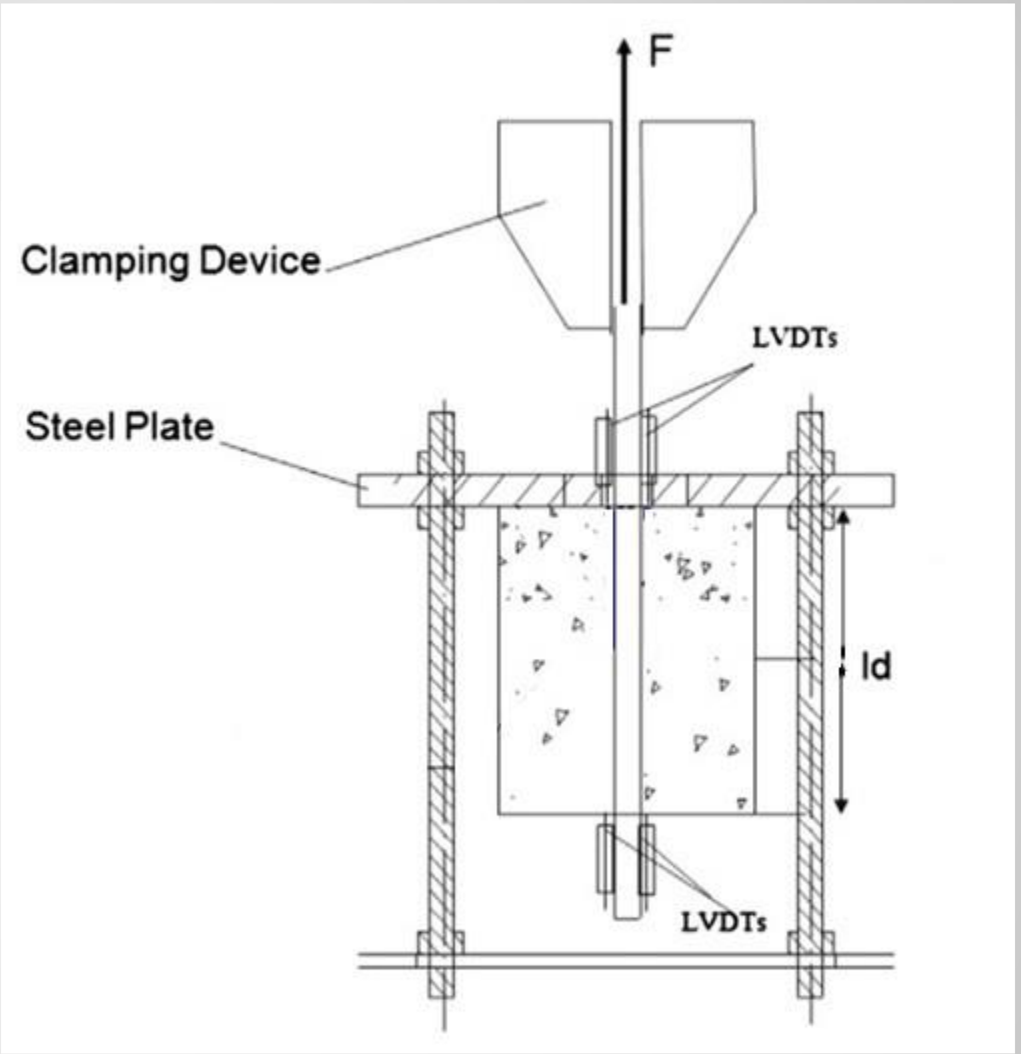
Specimens curing

CFRP bars: deep embedment

Pullout test

Pull-out test details

Pullout test set up in the laboratory



Schematic diagram

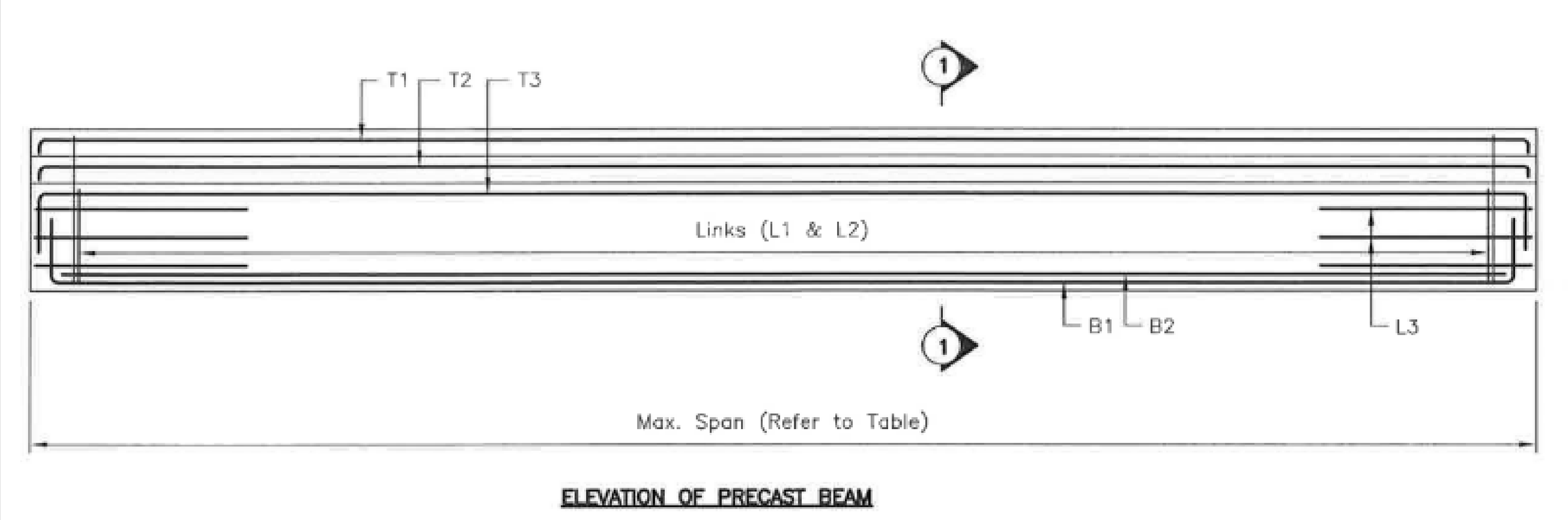
Flexural test details

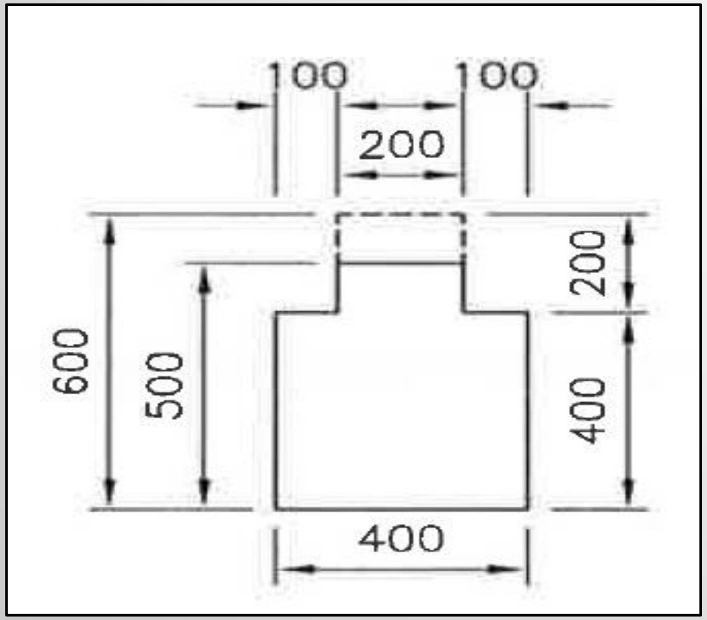
	Beam size						Top reinforcement			Bottom reinforcement		Links		
Beam*#	W (mm)	W_{UB} (mm)	H_T (mm)	H_C (mm)	H_B (mm)	Span (mm)	T1	T2	T3	B1	B2	L1 (boot)	L2 (main)	L3
BT-400600-4ST	400	200	600	500	400	4500	2H12	2H12	2H12	4H16	-	H10-250	H10-200	3H12 @ 100 c/c
BT-400600-4CFRP	400	200	600	500	400	4500	2H12	2H12	2H12	4CFRP8	-	H10-250	H10-200	3H12 @ 100 c/c
BT-400600-6CFRP	400	200	600	500	400	4500	2H12	2H12	2H12	6CFRP8	-	H10-250	H10-200	3H12 @ 100 c/c

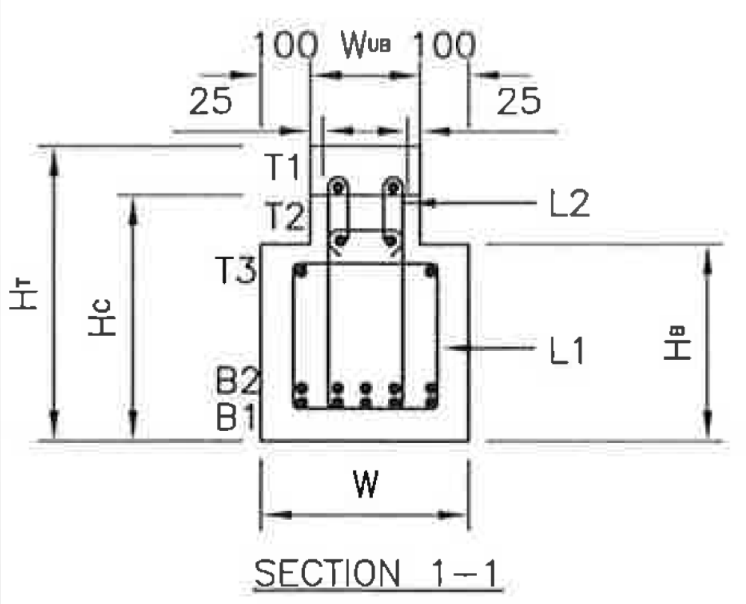
Notes: * - Each set encompass of three identical specimens.
- Average compressive strength for each beam at 28-days = 42.5 MPa

Specimen notations: 1) BT – Inverted-T beam;
2) 400600 – beam's width and depth;
3) 4ST – 4 steel bars reinforcement;
4) 4CFRP – 4 CFRP bars reinforcement;
5) 6CFRP – 6 CFRP bars reinforcement.

Inverted-T precast beam







Inverted-T precast beam

Aluminum tubes at both ends = 6 mm (thickness), 25.4 mm (outer diameter), 450 mm (length)

CFRP bars: coated with Sikadur-30 (average of 1 mm thickness) and installed with additional anchorage (aluminum tube)

The reinforcement of inverted-T precast beams

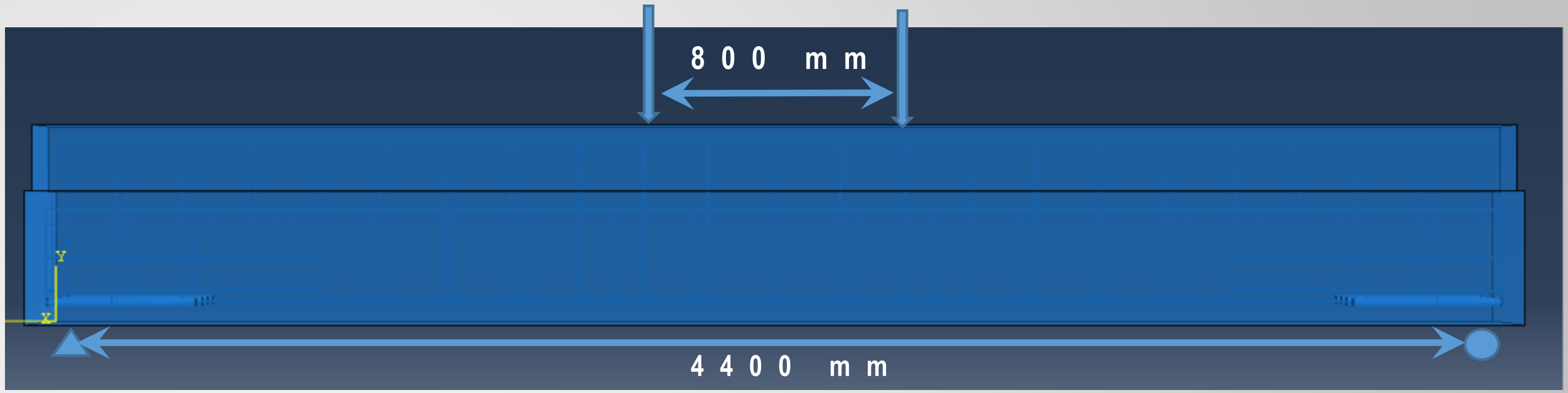
Inverted-T precast beam

Precast beam ready to concrete

Concreting works

Inverted-T precast beam

Four points flexural test set up in the laboratory



Schematic diagram

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Results and Discussions

Pull-out test results

Notation	Surface Type	f_c (MPa)	$\sqrt{f_c}$ (MPa)	Bonded Length, L_d (mm)	Diameter, d_b (mm)	Bond Strength, τ (MPa)*	Normalised Bond Strength, $\tau/\sqrt{f_c}$ ($MPa^{0.5}$)*	Loaded-end Slip, s_m (mm)*	Failure Mode
C1-S-C	Smooth	48.22	6.94	150	8	0.51	0.07	0.11	Bar pulled-out
C2-EC-C	Epoxy coated	48.22	6.94	150	8	5.22	0.75	2.54	Bar pulled-out
C3-EC-E	Epoxy coated	48.22	6.94	150	8	4.93	0.71	2.16	Bar pulled-out
C4-DE-C	Deep embedment	42.30	6.50	150	8	11.11	1.71	4.24	Bar pulled-out
C5-DE-E	Deep embedment	42.30	6.50	150	8	10.17	1.56	3.84	Bar pulled-out
C6-AA-C	Epoxy coated + AA	42.30	6.50	150	8	12.27	1.89	2.21	Bar pulled-out
C7-AA-E	Epoxy coated + AA	42.30	6.50	150	8	10.47	1.61	1.20	Bar pulled-out

Note: * - The average results are based on three identical specimens.

The average bond strength results of the specimen of C6-AA-C have achieved the minimum requirement of 12 MPa in bond strength for these modified smooth CFRP bars to be applied as flexural reinforcement (Benmokrane et al., 2002).

Flexural strength and aspect of behavior

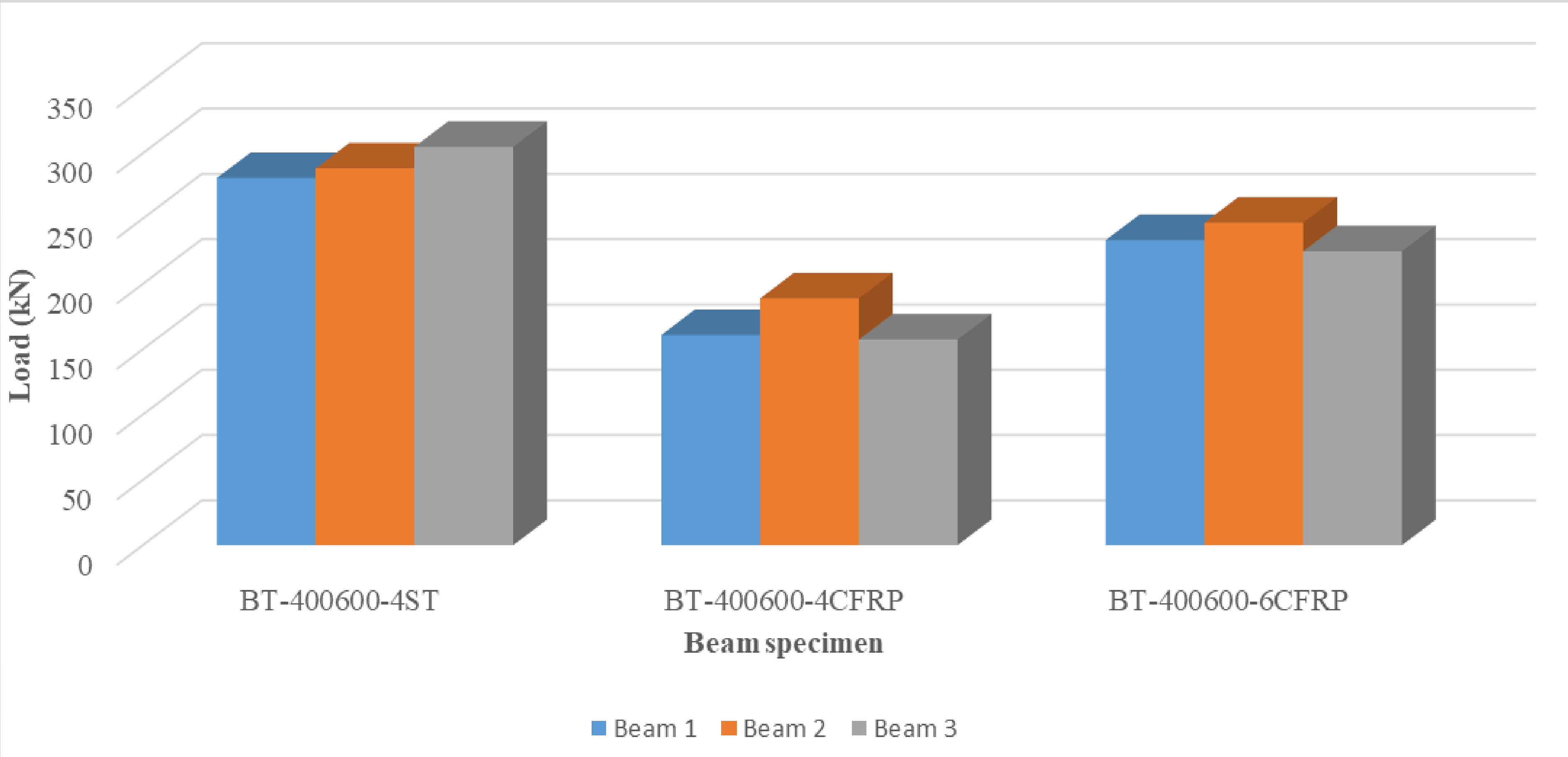
1) Summary of flexural strength test;
2) Ultimate loads;
3) Cracking moment and flexural moment capacity;
4) Failure mode;
5) Load-deflection behavior;
6) Neutral axis to depth ratio;
7) Cracking pattern and crack width;
8) Strain in concrete and CFRP bars.

Summary of flexural strength test

Group	Beam notation	First crack load, P_{cr} (kN)	Ultimate load, P_u (kN)	Deflection, Δ			Reinforcement ratio (ACI), ρ_f (ρ_f/ρ_{fb})	Mode of failure
				at P_{cr} (mm)	at $P_{35\%}$ (mm)	at P_u (mm)		
Group A – 4 steel bars reinforcement	BT-400600-4ST-1	64.87	281.05	2.60	5.08	36.15	0.0038 (0.22)	Tension failure
	BT-400600-4ST-2	70.17	288.37	3.04	6.26	36.03	0.0038 (0.22)	Tension failure
	BT-400600-4ST-3	61.71	304.90	2.71	7.37	33.29	0.0038 (0.22)	Tension failure
Group B – 4 CFRP bars reinforcement	BT-400600-4CFRP-1	65.25	160.91	1.91	6.28	33.91	0.00093 (0.66)	Tension failure
	BT-400600-4CFRP-2	57.29	188.92	2.56	9.45	44.52	0.00093 (0.66)	Tension failure
	BT-400600-4CFRP-3	58.29	157.37	1.48	10.84	44.19	0.00093 (0.66)	Tension failure
Group C – 6 CFRP bars reinforcement	BT-400600-6CFRP-1	65.29	233.47	2.02	7.06	45.69	0.00139 (0.99)	Tension failure
	BT-400600-6CFRP-2	65.58	246.85	2.45	7.28	43.87	0.00139 (0.99)	Tension failure
	BT-400600-6CFRP-3	62.59	225.03	1.29	10.55	*-	0.00139 (0.99)	Tension failure

Note: * - The LVDT was not working properly towards the end of the test.

Ultimate loads



Observations:

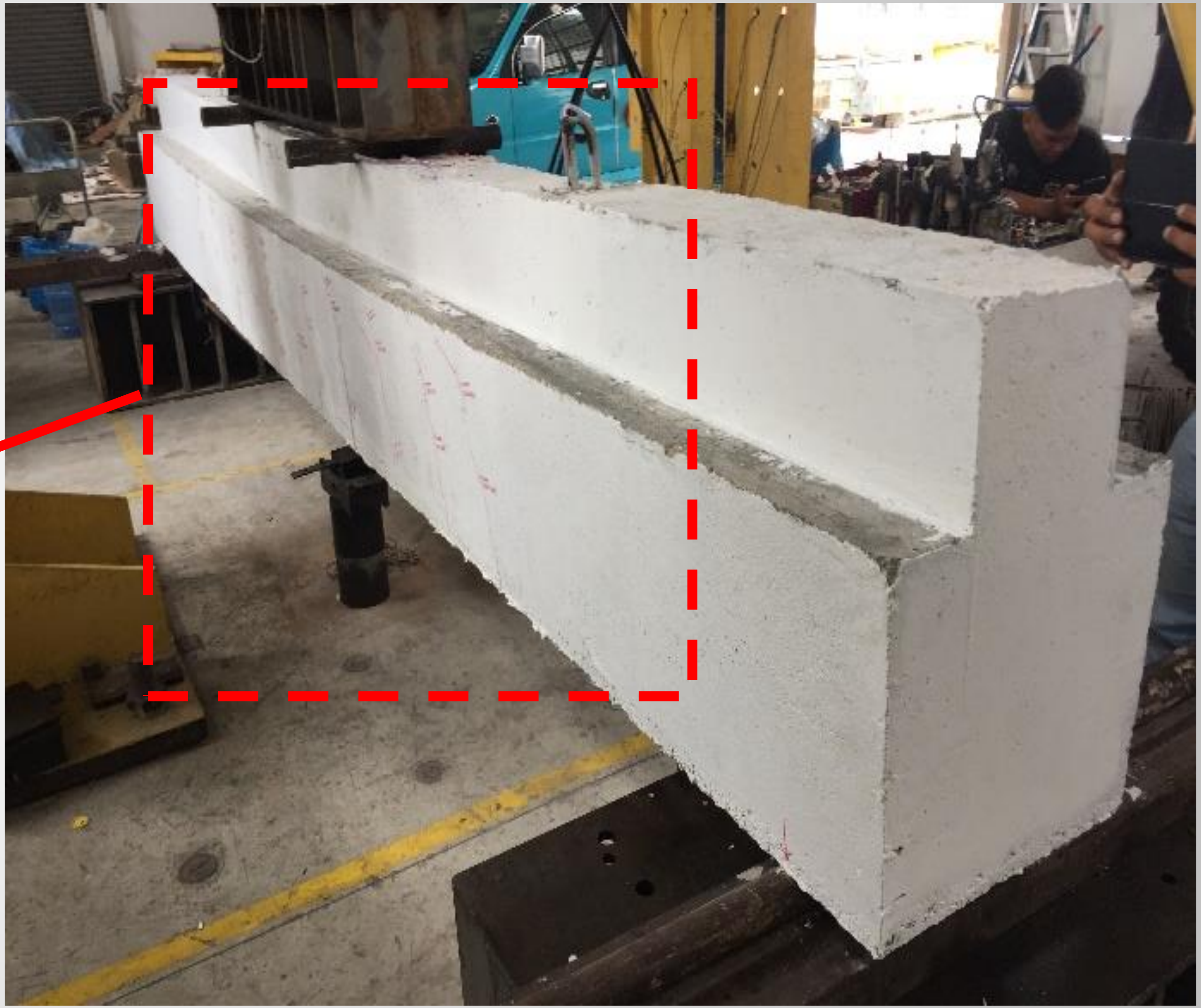
1) Increase CFRP reinforcement ratio: enhance ultimate load (45% - 55%) and control deflection.
2) Lower modulus of elasticity: Reduce the ultimate load of CFRP precast beams

Cracking moment and flexural moment capacity

Beam	Experiment (kNm)		Prediction (ACI) (kNm)		Ratio	
	M_{cr}	M_n	M_{cr}	M_{cap}	$M_{cr, exp}/M_{cr, pre}$	$M_{n, exp}/M_{cap, pre}$
BT-400600-4ST-1	56.8	170.6*	74.4	172.8	0.76	0.99
BT-400600-4ST-2	61.4	187.9*	74.4	172.8	0.83	1.09
BT-400600-4ST-3	54.0	188.3*	74.4	172.8	0.73	1.09
BT-400600-4CFRP-1	57.1	140.8	74.4	283.0	0.77	0.50
BT-400600-4CFRP-2	50.1	165.3	74.4	283.0	0.67	0.58
BT-400600-4CFRP-3	51.0	137.7	74.4	283.0	0.69	0.49
BT-400600-6CFRP-1	57.1	204.3	74.4	408.4	0.77	0.50
BT-400600-6CFRP-2	57.4	216.0	74.4	408.4	0.77	0.53
BT-400600-6CFRP-3	54.8	196.9	74.4	408.4	0.74	0.48

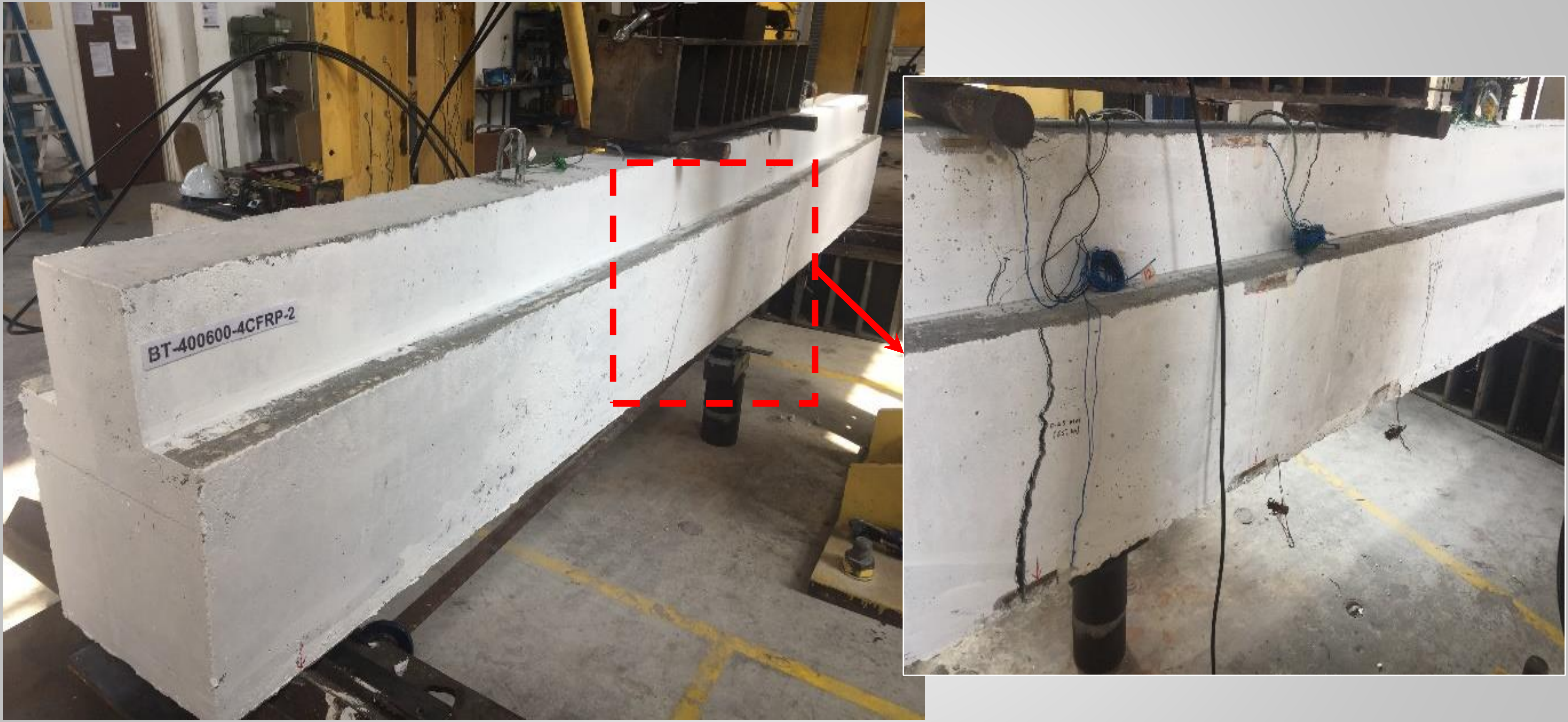
Note: *Moment corresponding to steel yielding

Failure mode (BT-400600-4ST beam)



Tensile failure with numerous flexural cracks at pure bending moment region

Failure mode (BT-400600-4CFRP beam)

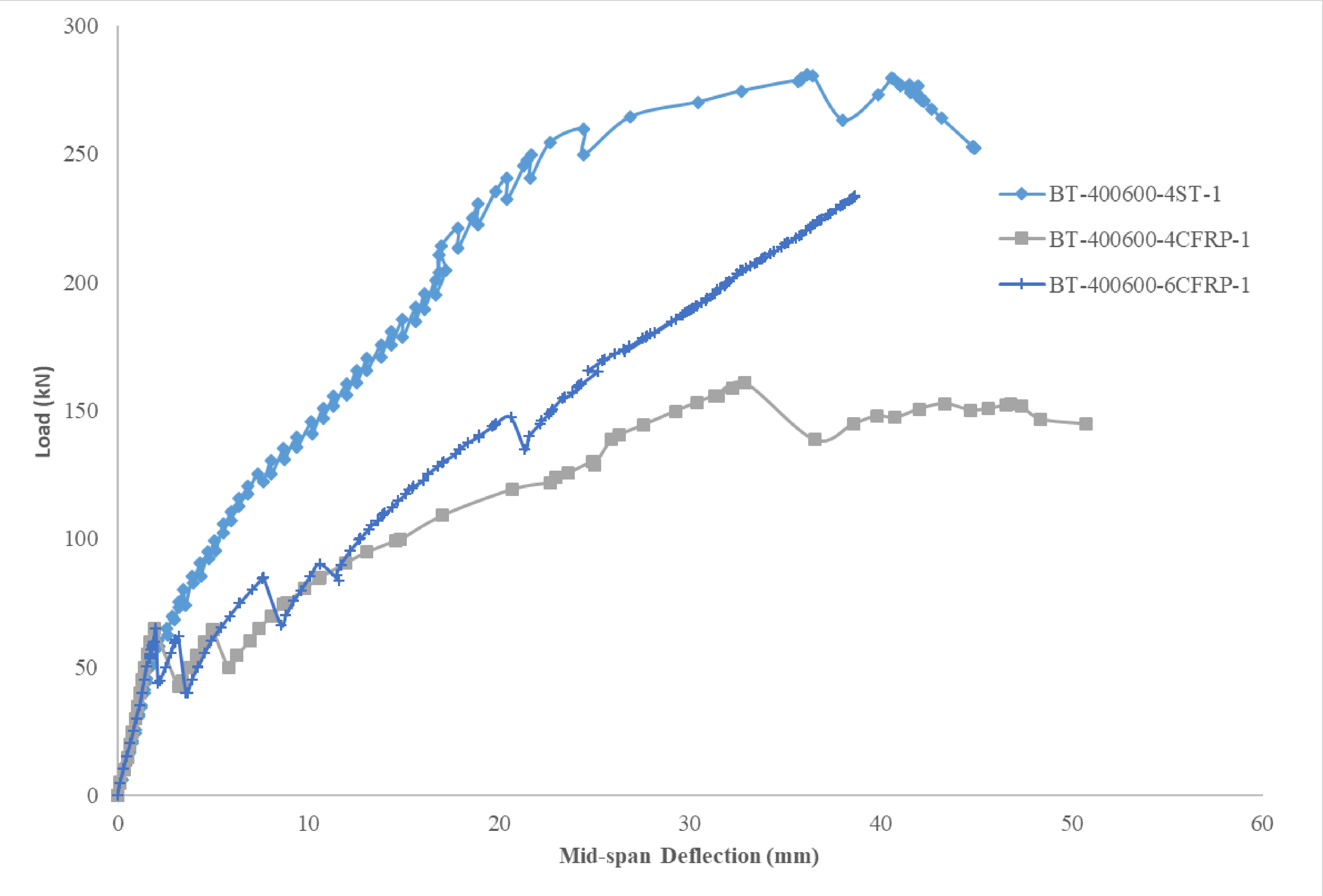


Tensile failure with several flexural cracks at pure bending moment region

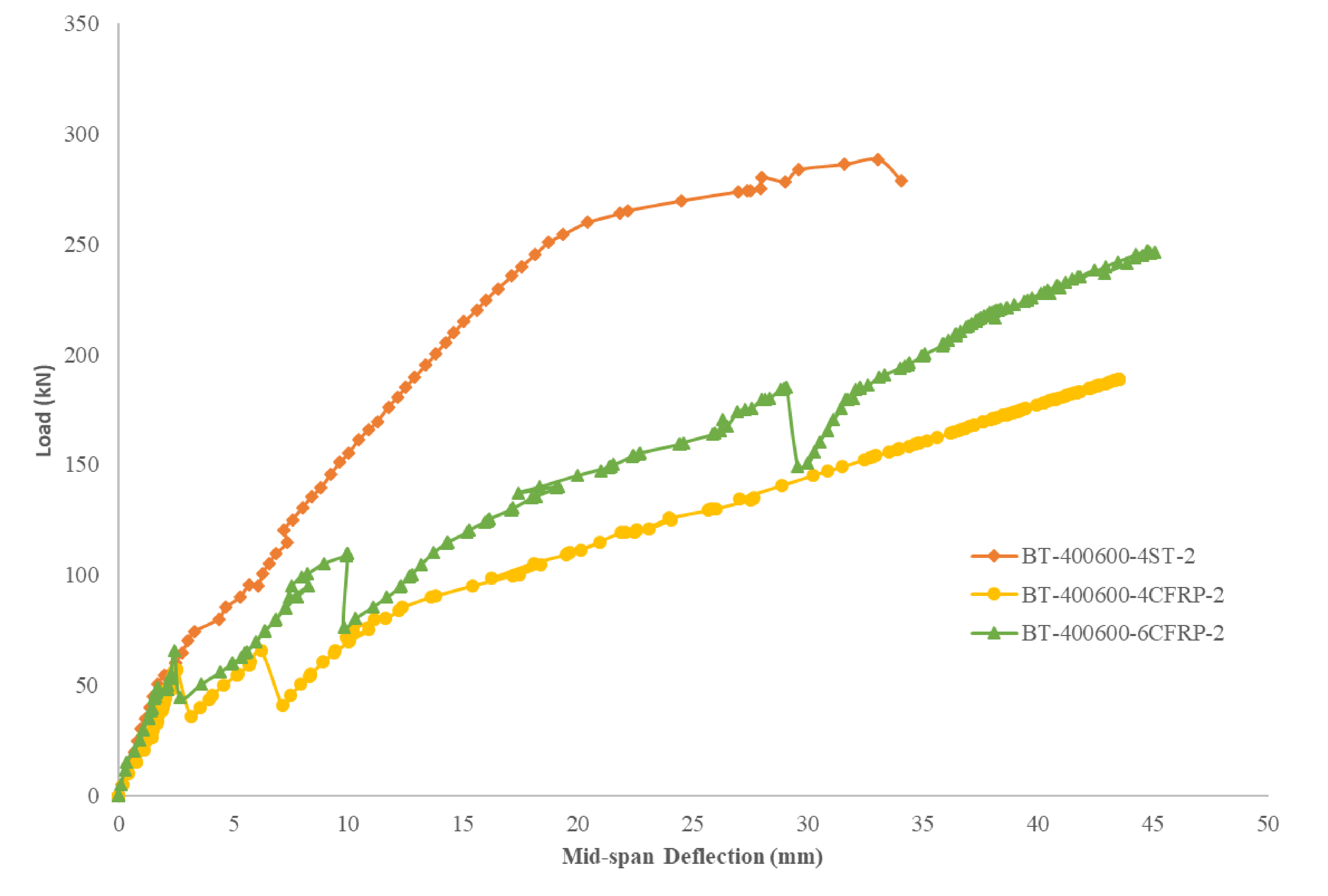
Failure mode (BT-400600-6CFRP beam)

Tensile failure with several flexural cracks at pure bending moment region

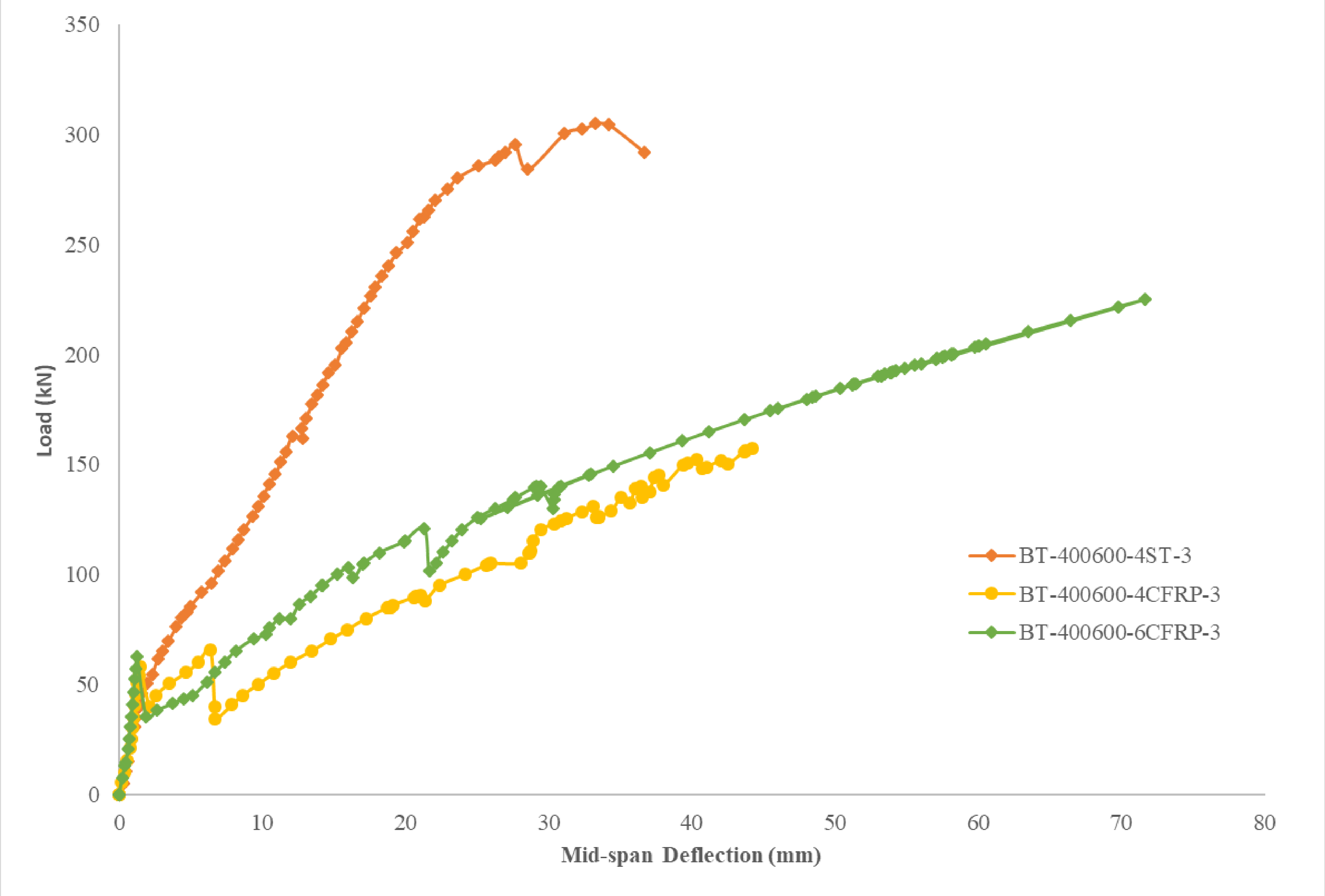
Load-deflection behavior (beam-1 series)



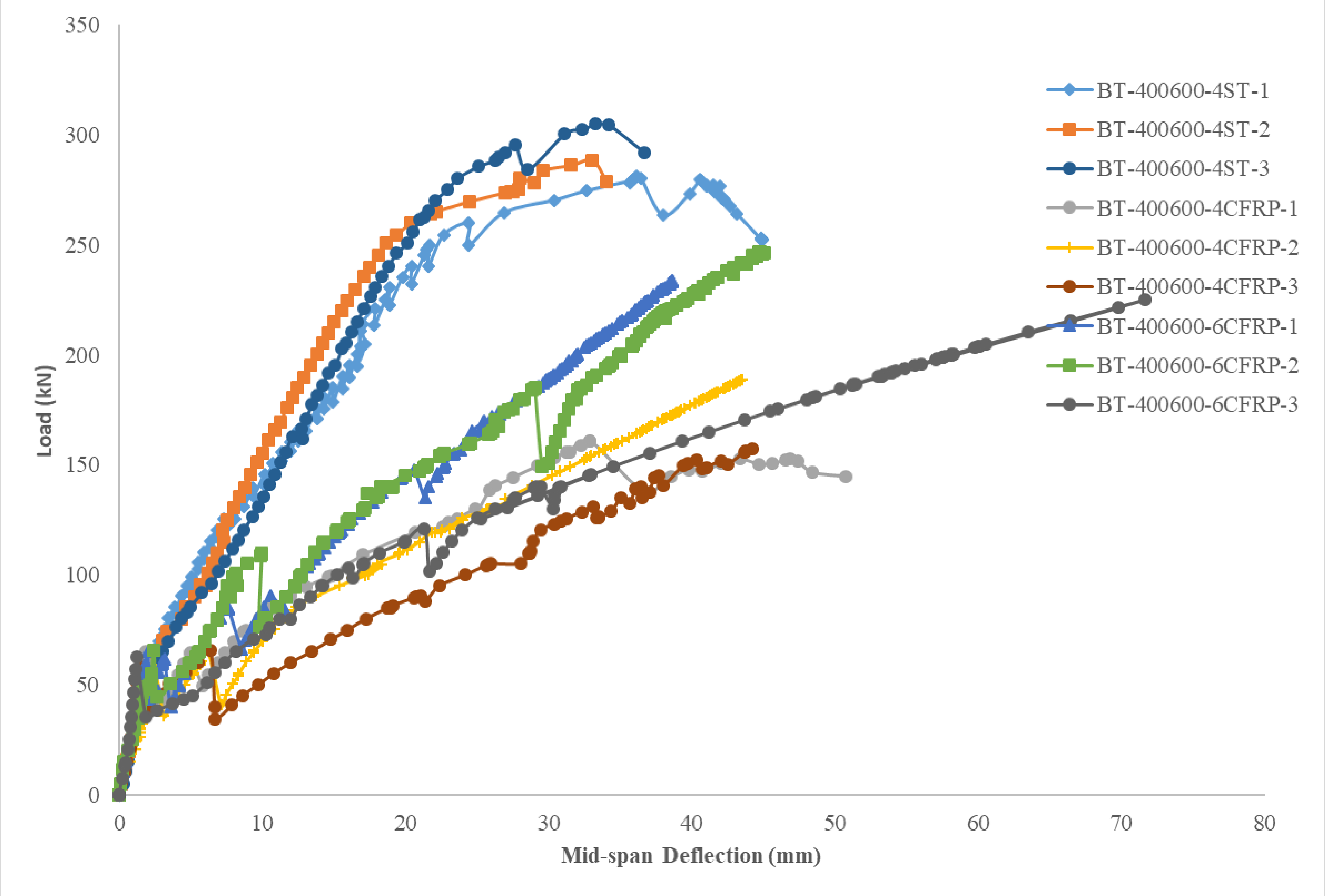
Load-deflection behavior (beam-2 series)



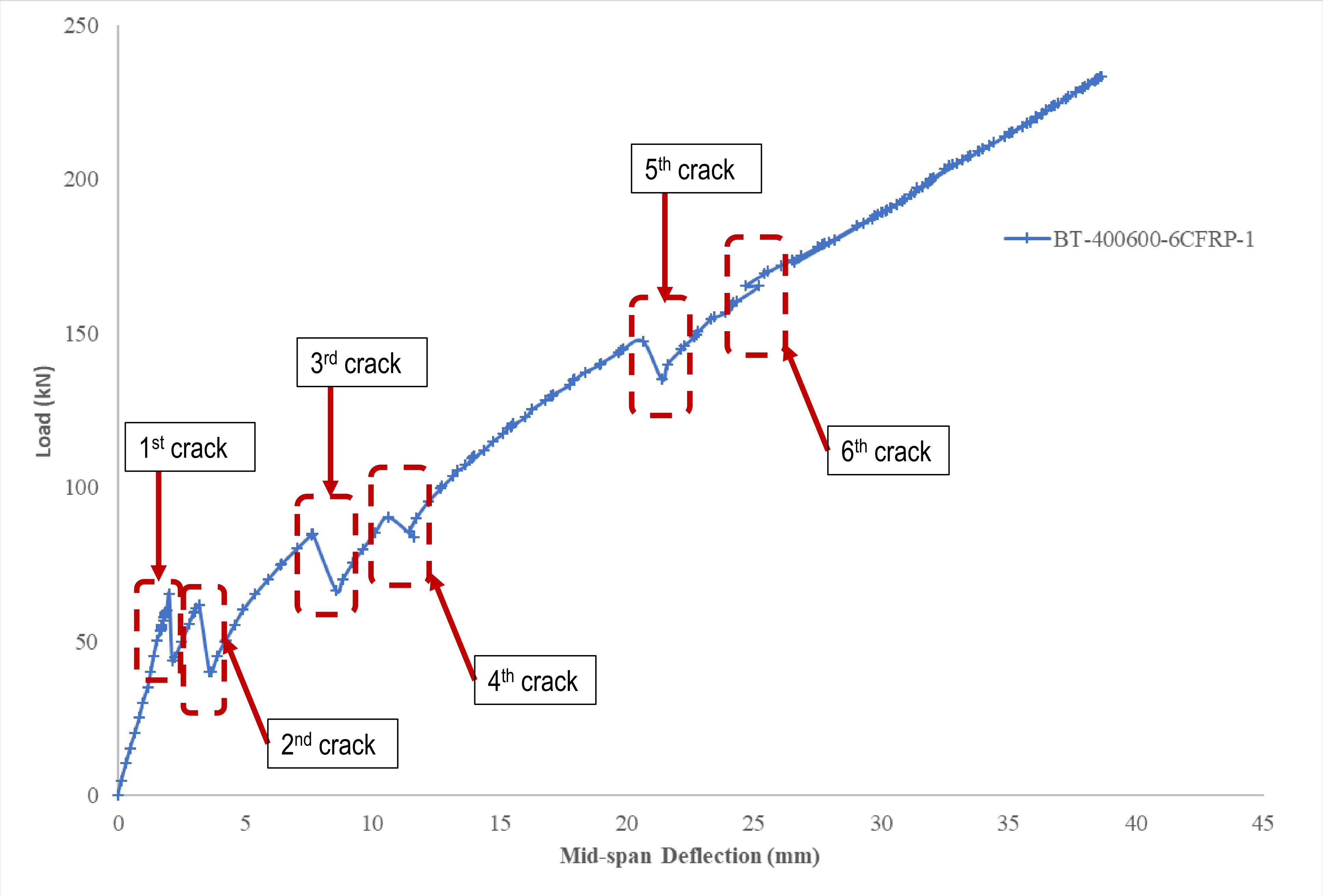
Load-deflection behavior (beam-3 series)



Load-deflection behavior (combined all beams)



Load-deflection behavior (BT-400600-6CFRP-1)

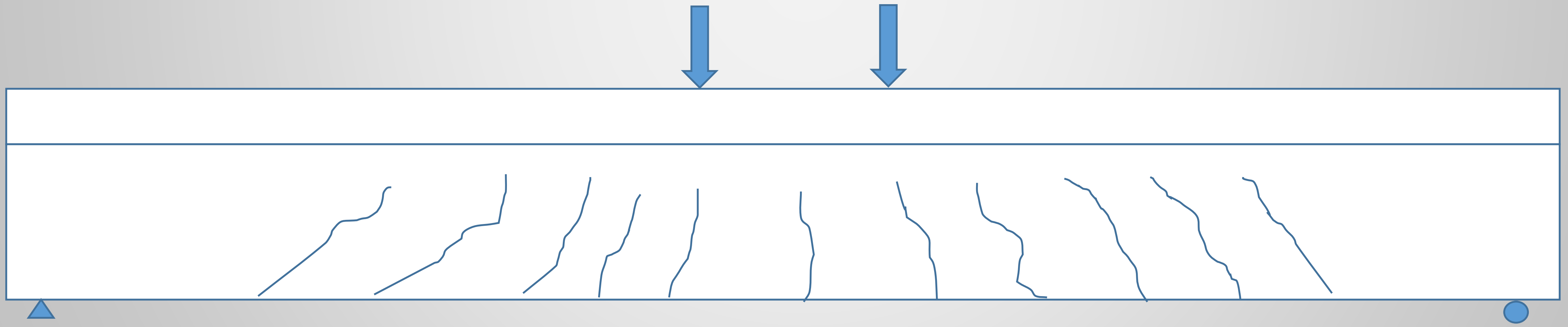


Neutral axis to depth ratio and curvature

Beam notation	Neutral axis to depth ratio (c/d)						Neutral axis at M_n (c/d)
	1st crack (before/after)	2nd crack (before/after)	3rd crack (before/after)	4th crack (before/after)	5th crack (before/after)	6th crack (before/after)	
BT-400600-4CFRP	0.55/0.24	0.21/0.17	0.18/0.21	-	-	-	0.19
BT-400600-6CFRP	0.47/0.44	0.41/0.32	0.26/0.26	0.23/0.23	0.24/0.24	0.26/0.27	0.28

Cracking numbers, spacing and width

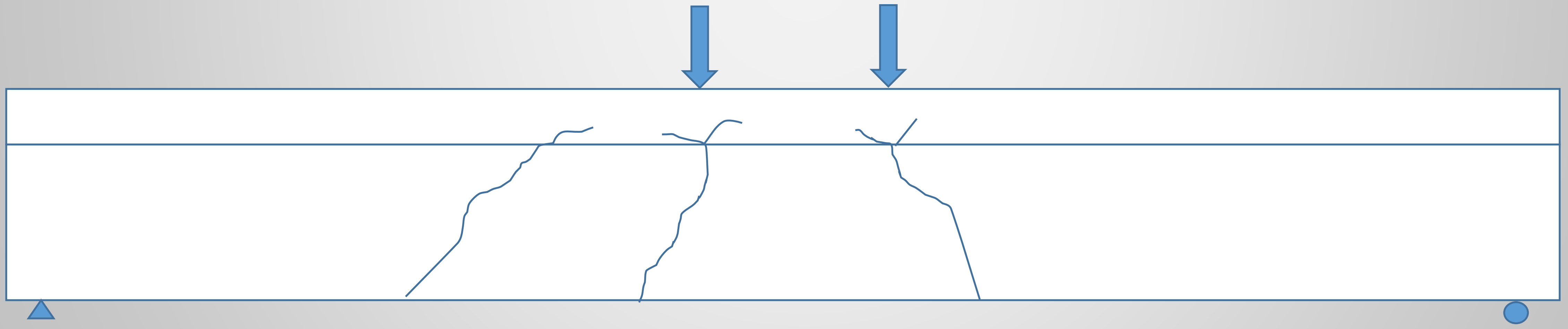
Beam notation	Number of cracks	Average crack spacing (mm)	Average crack width (mm)
BT-400600-4ST-1	11	260	2.0
BT-400600-4ST-2	12	263	2.3
BT-400600-4ST-3	13	255	2.5



BT-400600-4ST-1

Cracking numbers, spacing and width

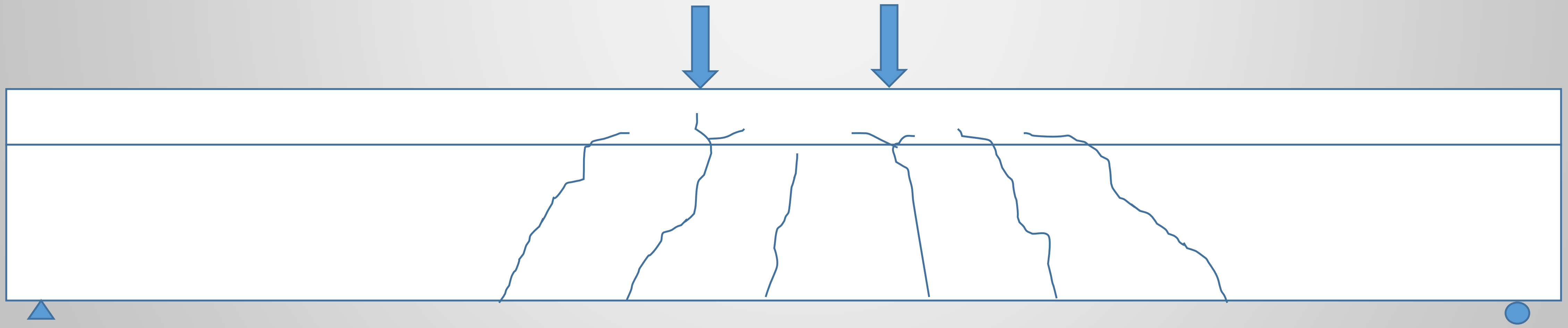
Beam notation	Number of cracks	Average crack spacing (mm)	Average crack width (mm)
BT-400600-4CFRP-1	3	1200	14.5
BT-400600-4CFRP-2	2	1100	14.0
BT-400600-4CFRP-3	3	1000	16.0



BT-400600-4CFRP-1

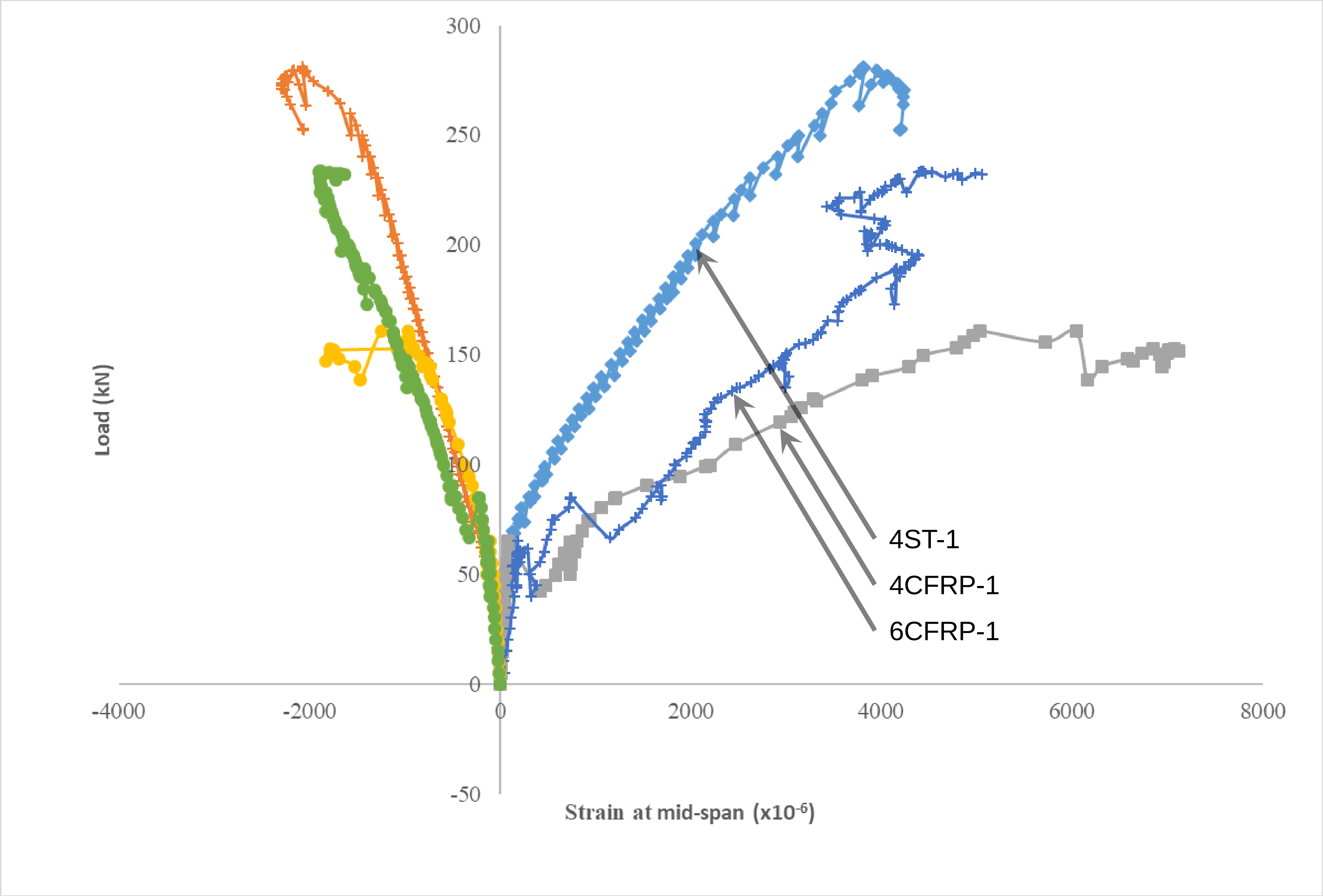
Cracking numbers, spacing and width

Beam notation	Number of cracks	Average crack spacing (mm)	Average crack width (mm)
BT-400600-6CFRP-1	6	670	7.06
BT-400600-6CFRP-2	7	590	10.2
BT-400600-6CFRP-3	5	710	9.0



BT-400600-6CFRP-1

Strain in concrete and CFRP bars (beam-1 series)



Conclusions

- **Prior to 1st crack:** CFRP precast beams are stiffer than steel precast beams;
- **Cracking load:** All beams have recorded nearly the same load;
- **At cracking load:**
  a) CFRP precast beams have exhibited sudden drop. The crack numbers can be easily identified from the graph (refer to load-deflection curve for the beam BT-400600-6CFRP-1;
  b) The sudden drop has negatively affected the beam stiffness, which increases the deflection, and the neutral axis moves deeply into the compression zone.
- **Deflection:**
  a) CFRP reinforced beams deflected more than steel reinforced beams after cracking.
  b) However, after steel yielded, deflection rate in steel reinforced beams are more than CFRP specimens;
- **Reinforcement ratio:** Precast beam reinforced with 6 CFRP bars recorded lower deflection as compared to the beams reinforced with 4 CFRP bars;
- **Failure mode:** No de-bond failure between CFRP bars and concrete. Hence, it is proven that this type of surface modification provide sufficient bond and anchorage so that smooth CFRP bars can be applied as flexural reinforcement;
- **Compressive strength:** Higher concrete strength potentially increase the first cracking load.

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THANK YOU

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