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Debonding-Related Strain Limits for Externally Bonded FRP Sheets in Flexurally Strengthened Reinforced Concrete Beams

Guibing Li[1,*], Aihui Zhang[2] and Yugang Guo[3]

[1]*College of Management Science and Engineering, Shandong Institute of Business & Technology, Yantai 264005, China*

[2]*College of Civil Engineering & Architecture, Zhejiang University, Hangzhou 310058, China*

[3]*International Business College, Shandong Institute of Business and Technology, Yantai, 264005, China*

Abstract: Debonding problems of externally bonded fiber reinforced polymer (FRP) sheets in flexurally FRP-strengthened reinforced concrete (RC) beams have been a concern and a research challenge since their application of this strengthening technique. Intermediate crack induced debonding is the most common failure mode which is that the debonding initiates at the critical flexural-shear or flexural cracks and propagates towards the direction of moment decrease. To mitigate debonding failure, most Codes and proposed models take the method by limiting the allowable tensile strain in FRP laminates. This paper presents experimental tests of concrete beams flexurally strengthened with externally bonded CFRP sheets to investigate debonding initiation and tensile strain of FRP laminates. The allowable tensile strain of FRP sheets in flexurally FRP-strengthened RC beams proposed by prevalent Code provisions and models was assessed based on the data obtained from experimental programs. It has beenshown that the allowable tensile strains provided by these provisions and models have a great difference with that of experimental results and exhibit a high level of dispersion. Furthermore, the FRP laminates of most tested RC beams were debonded before reaching the proposed allowable tensile strain. The Code provisions and models are inadequate to effectively prevent intermediate crack induced debonding failure in flexurally FRP-strengthened RC members. This is known to be a critical issue in engineering design and application of RC beams flexurally strengthened by FRP sheets.

Keywords: RC Beam, FRP sheet, strengthening, debonding failure, allowable tensile strain.

INTRODUCTION

Debonding of externally bonded fiber reinforced polymer (FRP) sheets used for the rehabilitation and retrofitting of reinforced concrete flexural members has been commonly observed. The most commonly reported debonding mode in experimental literatures is the debonding initiates at critical flexural/shear and flexural cracks near the region of maximum moment. This failure mode of debonding is properly termed as intermediate crack-induced debonding. The prevalent Code provisions [1-6] and proposed models [7-10] for the design of externally bonded FRP systems often take the method by limiting the tensile strain or stress in the FRP laminates to mitigate debonding. Based on the tests results of flexurally FRP-strengthened RC beams failed cause of intermediate crack-induced debonding failure, this paper carried out a comprehensive comparison of the Code provisions and models and evaluated their validity and accuracy.

EXPERIMENTAL PROGRAM

8 simply supported beams, including A2 and B2 series, and 9 cantilever beams, including B1e, B2e and B2i series, were tested to investigate debonding process and tensile strain of FRP laminates in flexurally FRP-strengthened RC beams. The test specimens, series A2 and B2, used in the experimental program were prepared with varying properties: amount of tensile reinforcement and carbon fiber reinforced polymer (CFRP) sheets, preload level; for series B1e, B2e and B2i, the test variables are amount of CFRP sheets, preload level and anchorage method, respectively, see Table **1**. Properties of materials used in these specimens are listed in Table **2**. The mechanical properties of epoxy adhesive and CFRP sheets were provided by the manufacturer. The test set-ups and geometries of the tested beams are shown in Fig. (**1**) and Fig. (**2**).

TEST RESULTS

All the CFRP-strengthened RC beams failed by intermediate crack-induced debonding of CFRP laminates. The typical crack patterns of the strengthened beams are shown in Fig. (**3**). It can be observed during the test procedure that the width of the critical shear-flexural crack (CSFC) increased rapidly after the tension rebar yielding. Subsequently, a tributary crack formed adjacent to the CSFC, forming a triangular concrete block bounded by the CSFC, the tributary crack and the soffit of the beam; and then with the widening of the CSFC at beam soffit level was associated with the formation of a relative vertical displacement, as

*Address correspondence to the author at the College of Management Science and Engineering, Shandong Institute of Business & Technology, Yantai 264005, China; Tel: +86-535-6903575;
E-mails: liguibing@zju.edu.cn, leegb@sina.com

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Table 1. Specimens and Test Variables

Series	Beam	Rebar	CFRP (Plies)	Preload	Anchor Program
	A20*		2	0	—
A2	A23		2	$0.3P_y$	—
	A26		2	$0.6P_y$	—
	A28		2	$0.8\,P_y$	—
B2	B20		2	0	—
	B26		2	$0.3P_y$	—
	B28		2	$0.6P_y$	—
	B23		2	$0.8\,P_y$	—
B1e	B10e		1	0	external
	B13e		1	$0.3P_y$	external
	B16e		1	$0.6P_y$	external
B2e	B20e		2	0	external
	B23e		2	$0.3P_y$	external
	B26e		2	$0.6P_y$	external
B2i	B20i		2	0	internal
	B23i		2	$0.3P_y$	internal
	B26i		2	$0.6P_y$	internal

*the first number denotes plies of CFRP laminates; the second number denotes the preload level corresponding to 0, $0.3P_y$, $0.6P_y$ and $0.8P_y$; and e and i denote external anchorage and internal anchorage, respectively.

Table 2. Properties of Materials

Beams	Strength(MPa)*			Modulus (GPa)	
	f_{cu}	f_{frp}	f_y	E_{frp}	E_s
B1e, B2e, B2i	55.8	4150	361	235	200
A2, B2	23.0	3550	378	235	200
b1, b2 [11]	35.0	3500	288	235	200
S1a [12]	47.7	3900	504	213	192

*f_{cu}- concrete cubic compressive strength; E_s、E_{frp}- modules of tension rebar and FRP laminates respectively; f_y-yield strength of tension rebar; f_{frp}- tension strength of FRP.

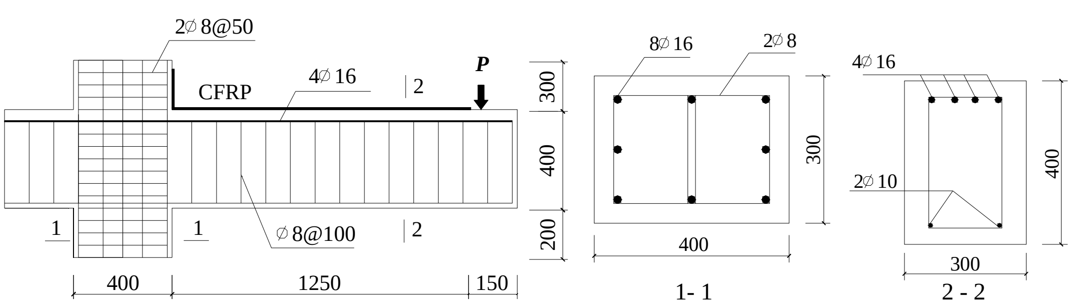

Fig. (1). Specimen details and reinforcement arrangement (for B1e, B2e, and B2i).

shown in Fig. (**4**), between the two halves of the CSFC, and the relative displacement became more pronounced with further load applied on the beam. When the relative displacement reached to a critical magnitude, debonding of CFRP sheets initiated at the tip of the tributary crack and propagated towards the laminates end. Fig. (**5a-d**) illustrates the whole debonding procedure of CFRP sheets.

Figs. (**6-10**) show the relationships of load-tensile strain in the CFRP laminates of series A2, B2, B1e, B2e and B2i respectively. The tensile strains in CFRP laminates of the

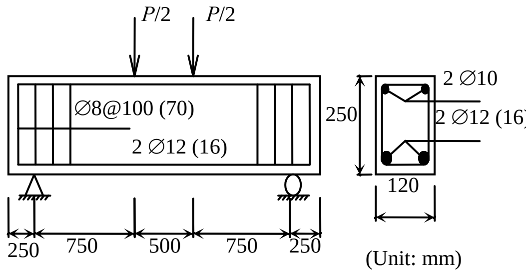

Fig. (2). Specimen details and reinforcement arrangement(for A2 and B2).

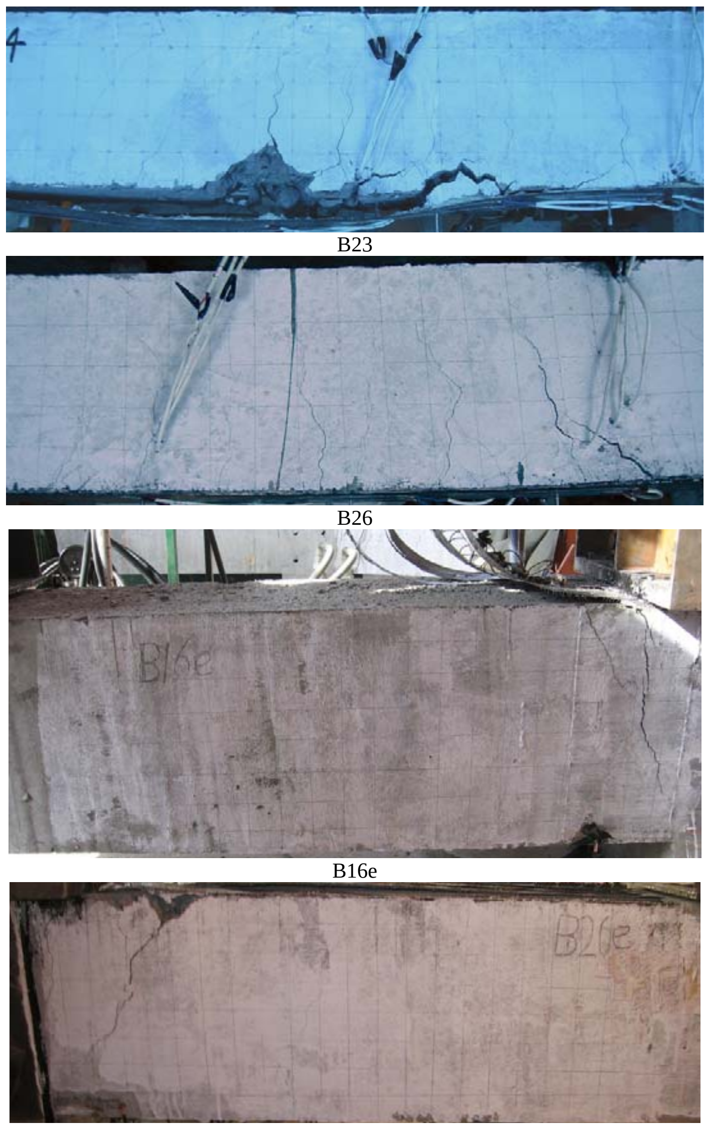

Fig. (3). Crack pattern of Beam B23, B26, B16e, and B26e.

strengthened beams at initial debonding $\varepsilon_{fd,tested}$ are listed in Table **3** and Table **4**, and illustrated in Fig. (**11**) and Fig. (**12**), respectively.

PREVALENT MODELS PRESENTED IN CODES AND LITERATURES

To prevent intermediate crack-induced debonding failure in flexurally FRP-strengthened RC members, most codes and proposed models define the approach that tensile strain in FRP sheets should be limited to a threshold value at which debonding of FRP sheets may occur. The prevalent Code provisions and proposed models for determining the allowable tensile strain in FRP sheets, ε_{fd}, are summarized in Table **5**.

ACI 440.2R-08 [1] describes a modification of the debonding strain equation proposed by Teng *et al*.[7, 10] that

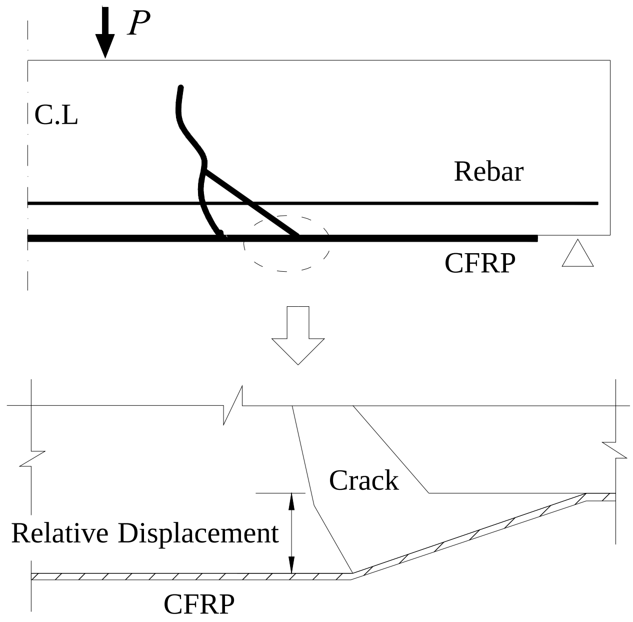

Fig. (4). Close-up view at the tip of tributary crack.

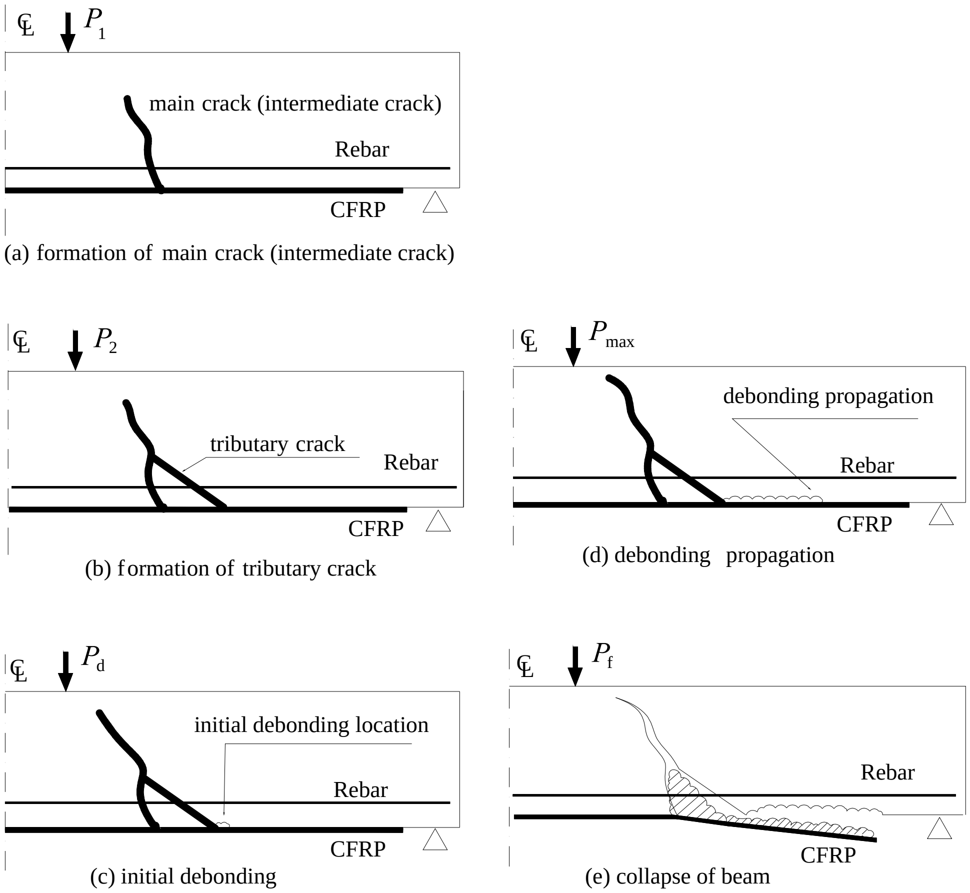

Fig. (5). Debonding process of CFRP laminates.

was based on the investigation of a significant database of flexural member tests exhibiting FRP sheets debonding failure. The proposed equation was calibrated using average values of FRP tensile strains measured at debonding and the database for flexural tests experiencing intermediate crack-induced debonding was used to determine the best fit coefficient of 0.41.

JSCE recommendations [5] suggested that debonding of FRP sheets does not take place when the stress in FRP sheets at the location of flexural crack caused by the maximum

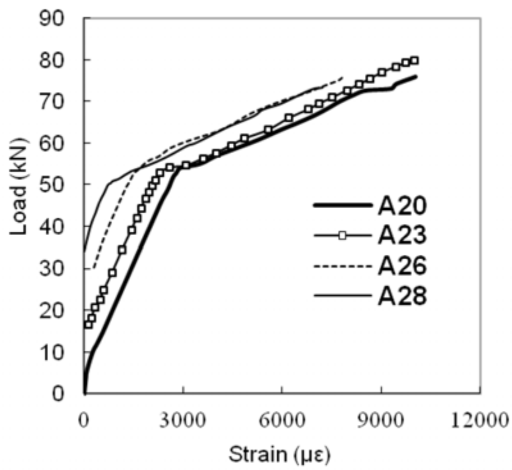

Fig. (6). Load6-FRP strain relationship of series A2.

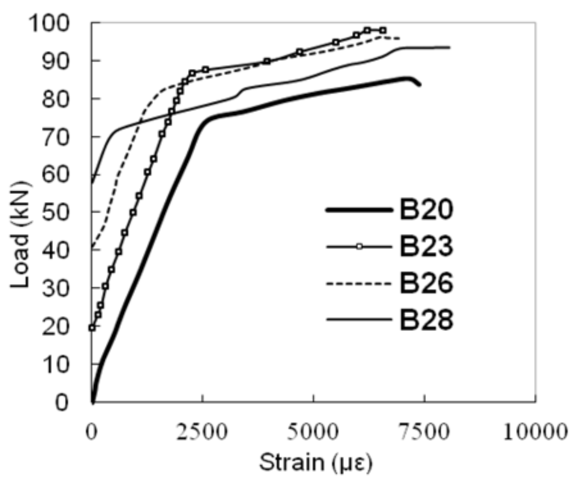

Fig. (7). Loa-FRP strain relationship of series B2.

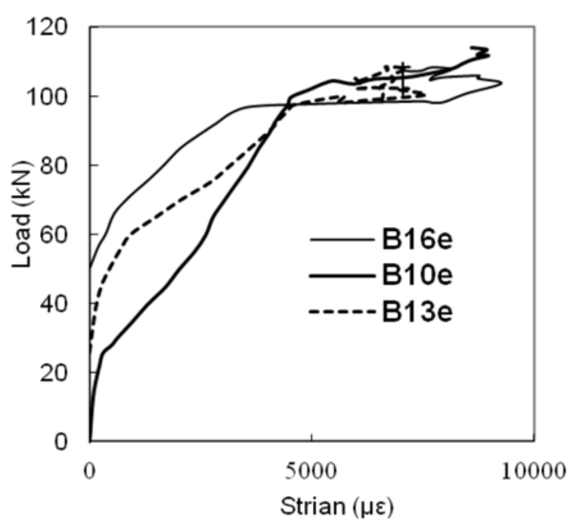

Fig. (8). Load-FRP strain relationship of series B1e.

bending moment in the member satisfies $\sigma_f \leq \sqrt{2G_f E_f / t_f}$, and also suggested that the flexural capacity and axial load-carrying capacity of members failing due to debonding of FRP sheets may be calculated by the maximum value for the difference in tensile stress occurring

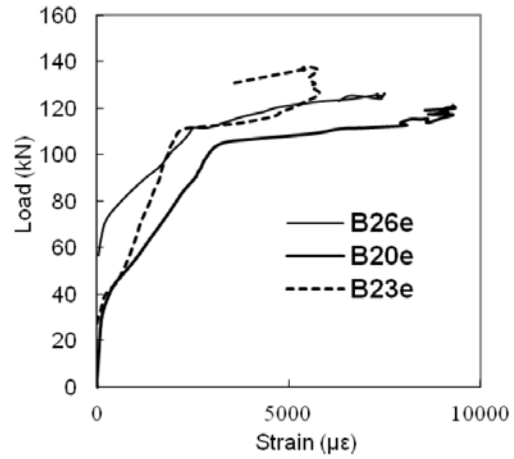

Fig. (9). Load-FRP strain relationship of series B2e.

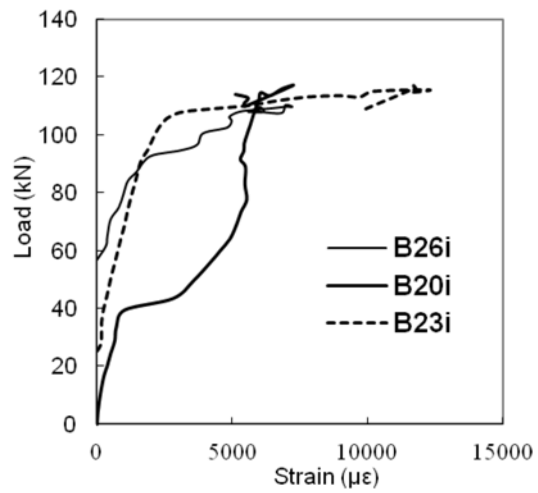

Fig. (10). Load-FRP strain relationship of series B2i.

in FRP sheets satisfy $\Delta\sigma_f \leq \sqrt{2G_f E_f / t_f}$. However, these FRP stress equations include an interfacial fracture energy (G_f) term for FRP-concrete interface. The G_f is determined by experimental results and accounted for many factors and aspects of design. However, the G_f determined by testing and experimental results is complex and not conducive to design process.

fib bulletin-14 [2] recommends using shear stress-slip relationships to predict debonding failure in flexurally FRP-strengthened RC members. Critical bond stress and slip parameters determined from analysis of experimental data were recommended. Bulletin 14 presents three approaches to mitigate debonding failure. The first approach (fib-1) limits the maximum allowable axial load in the FRP sheets and the length required to anchor this load. To account for the effect of width of FRP sheets and RC beam (b_f/b), a k_b factor is introduced. The second approach (fib-2) presents a critical crack pattern and the bond (adhesive) stresses this pattern would cause. Bond stresses rise between flexural cracks and these stresses are then transferred to FRP laminates. The fib-2 limits the maximum stress the FRP laminates can have transferred to it, and determines an anchorage length differently than the fib-1. These two approaches can be used

Table 3. Tested and Evaluated Tensile Strain in FRP Laminates at Initiation of Debonding (Code Models)

Beam	$\varepsilon_{fd,test}$	ε_{fd} (με)							$\varepsilon_{fd}/\varepsilon_{fd,test}$ (%)						
		ACI	JSCE	fib-1	fib-2	CECS	TR55	DT200	ACI	JSCE	fib-1	fib-2	CECS	TR55	DT200
A20	8971	7099	4378	2483	10555	10000	3217	5109	79	49	28	118	111	36	57
A23	8182	7099	4378	2483	10555	10000	3217	5109	87	54	30	129	122	39	62
A26	7805	7099	4378	2483	10555	10000	3217	5109	91	56	32	135	1.28	41	65
A28	6994	7099	4378	2483	10555	10000	3217	5109	102	63	36	151	1.43	46	73
B20	6253	7099	4378	2483	10555	10000	3217	5109	114	70	40	169	160	51	82
B23	5959	7099	4378	2483	10555	10000	3217	5109	119	73	42	177	168	54	86
B26	6489	7099	4378	2483	10555	10000	3217	5109	109	67	38	163	154	50	79
B28	6086	7099	4378	2483	10555	10000	3217	5109	117	72	41	173	164	53	84
B10e	8386	15637	6192	4425	20913	10000	5734	10122	186	74	53	249	119	68	121
B13e	7543	15637	6192	4425	20913	10000	5734	10122	207	82	59	277	133	76	134
B16e	7708	15637	6192	4425	20913	10000	5734	10122	203	80	57	271	130	74	131
B20e	5649	11057	4378	3129	14788	10000	4054	7157	196	78	55	262	177	72	127
B23e	5636	11057	4378	3129	14788	10000	4054	7157	196	78	56	262	177	72	127
B26e	6180	11057	4378	3129	14788	10000	4054	7157	179	71	51	239	162	66	116
B20i	6391	11057	4378	3129	14788	10000	4054	7157	173	69	49	231	156	63	112
B23i	6457	11057	4378	3129	14788	10000	4054	7157	171	68	48	229	155	63	111
B26i	7216	11057	4378	3129	14788	10000	4054	7157	153	61	43	205	139	56	99
b1	2520	7099	4378	2483	10555	9929	3217	5109	282	174	99	419	394	128	203
b2	3630	7099	4378	2483	10555	9929	3217	5109	196	121	68	291	274	89	141
S1a	2756	10031	4249	2929	13627	10000	3795	6595	364	154	106	494	363	138	239
Aver.									166	81	52	232	176	67	112
Cov.									41	39	39	40	43	39	40

Table 4. Tested and Evaluated Tensile Strain in FRP Laminates at Initiation of Debonding (Proposed Models)

Reference		ε_{fd} (με)					$\varepsilon_{fd}/\varepsilon_{fd,test}$ (%)			
	beam	$\varepsilon_{fd,test}$	Teng03	Lu	Wu	Teng04	Teng03	Lu	Wu	Teng04
present	A20	8971	3073	5281	6931	4006	34	59	77	45
	A23	8182	3073	5281	6931	4006	38	65	85	49
	A26	7805	3073	5281	6931	4006	39	68	89	51
	A28	6994	3073	5281	6931	4006	44	76	99	57
	B20	6253	3073	5281	6931	4006	49	84	111	64
	B23	5959	3073	5281	6931	4006	52	89	116	67
	B26	6489	3073	5281	6931	4006	47	81	107	62
	B28	6086	3073	5281	6931	4006	50	87	114	66
	B10e	8386	5435	11993	8364	6195	65	143	100	74

Table 4 Contd....

	B13e	7543	5435	11993	8364	6195	72	159	111	82
	B16e	7708	5435	11993	8364	6195	71	156	109	80
	B20e	5649	3843	8387	8012	6195	68	148	142	110
	B23e	5636	3843	8387	8012	6195	68	149	142	110
	B26e	6180	3843	8387	8012	6195	62	136	130	100
	B20i	6391	3843	8387	8012	6195	60	131	125	97
	B23i	6457	3843	8387	8012	6195	60	130	124	96
	B26i	7216	3843	8387	8012	6195	53	116	111	86
Yang[11]	b1	2520	3073	5559	7568	4520	122	221	300	179
	b2	3630	3073	5559	7568	4520	85	153	208	125
Pham[12]	S1a	2756	3771	9567	8243	7514	137	347	299	273
Aver.							64	130	135	94
Cov.							40	50	45	55

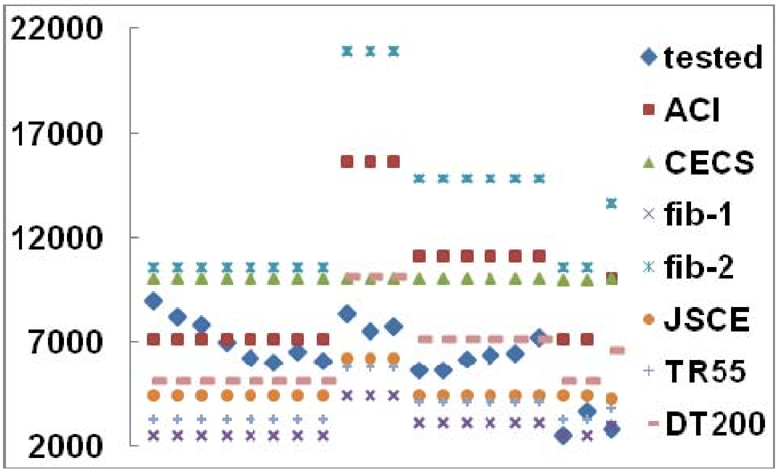

Fig. (11). Comparison of tested and predicted tensile strain in FRP laminates at initial debonding (Code models).

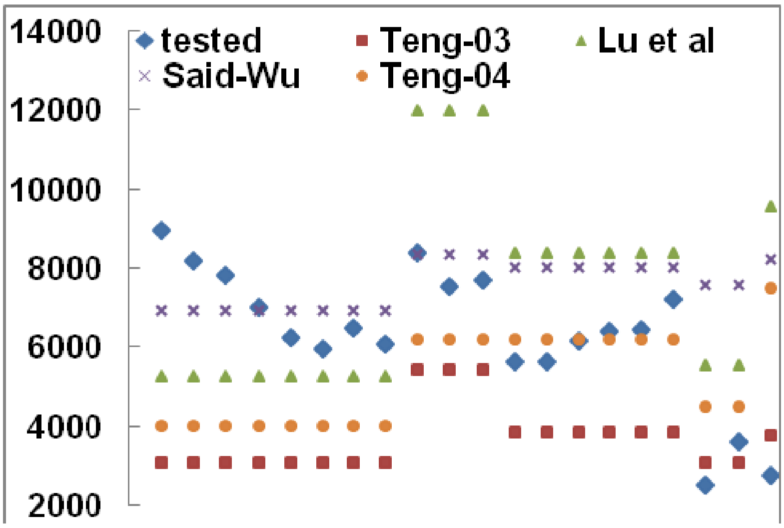

Fig. (12). Comparison of tested and predicted tensile strain in FRP laminates at initial debonding (proposed models).

to derive allowable tensile strain equations for FRP sheets in order that debonding is prevented. The third approach is very complex and is not suitable for engineering application, and therefore, it is not assessed with the present discussion.

CECS146 [6] suggested the effective tensile strain in FRP reinforcements to prevent intermediate crack-induced debonding failure. The allowable tensile strain of FRP laminate takes the product of thickness reduction factor, k_m, and the nominal ultimate tensile strain of FRP laminate, ε_{cfu}. Furthermore, the allowable tensile strain should not be greater than 2/3 ε_{cfu} or 0.01.

The Technical Report 55 (TR55) issued by the UK's Concrete Society [3], uses an approach similar to the fib-1 in the fib bulletin 14 to mitigate FRP laminates debonding in flexurally FRP-strengthened RC members.

To evaluate the maximum design intermediate crack-induced debonding tensile strain for FRP reinforcement, the Italian Code CNR DT200 [4] proposed a simplified method found based on a fracture mechanics approach.

Table 5. Models for Determining Allowable Tensile Strain εfd in FRP Laminates to Mitigate Intermediate Crack-induced Debonding

ACI 440	$\varepsilon_{fd} = 0.41\sqrt{f_c' / nE_f t_f} \le 0.9\varepsilon_{fu}$
JSCE	$\varepsilon_{fd} \le \sqrt{2G_f / E_f t_f}$
fib-1	$\varepsilon_{fd} = \alpha c_1 k_c k_b \sqrt{\dfrac{f_{ct}}{E_f t_f}}$
fib-2	$\varepsilon_{fd} = c_1 \sqrt{\sqrt{f_{ct} f_c'} / E_f t_f}$
CECS146	$\left[\varepsilon_{fd}\right] = \min\left\{ \left(1.16 - \dfrac{n_{cf} E_{cf} t_{cf}}{308000}\right)\varepsilon_{cfu} ,\ 2\varepsilon_{cfu}/3,\ 0.01 \right\}$
TR55	$\varepsilon_{fd} = 0.5 k_b \sqrt{f_{ct} / E_f t_f}$
DT200	$\varepsilon_{fd} = 0.484\sqrt{k_b \sqrt{f_c' f_{ct}} / nE_f t_f}$
Teng2003	$0.48\beta_L \sqrt{\left(2 - \dfrac{b_f}{b}\right) \Big/ \left(1 + \dfrac{b_f}{b}\right)} \sqrt{\dfrac{\sqrt{f_c'}}{E_f t_f}}$
Said-Wu	$\varepsilon_{fd} = 0.23 f_c'^{0.2} / \left(E_f t_f\right)^{0.35}$
Lu	$\varepsilon_{fd} = 0.114\left(4.41 - \alpha\right)\tau_{\max} / \sqrt{E_f t_f}$
Teng2004	$\dfrac{0.54 f_{ct}}{\sqrt{E_f t_f}} \sqrt{\left(2.25 - \dfrac{b_f}{b}\right) \Big/ \left(1.25 + \dfrac{b_f}{b}\right)}$

The Teng *et al*'s model (Teng2003) [7] simply modified the empirical model based on analogy between debonding failure in simple shear tests and intermediate crack-induced debonding failure. Teng2003 model considered the effect of concrete compressive strength and width ratio of FRP laminates and RC beam (b_f/b), in addition to FRP axial stiffness ($E_f t_f$), on the debonding failure.

In light of the maximum FRP tensile strain corresponding to the ultimate experimental load of each tested beam in the database and considering the effect of concrete compressive strength, Said and Wu [9] proposed a critical value for FRP tensile strain on the debonding failure.

Using dual local debonding criterion and different bond-slip models for major flexural crack zone and rest of a beam, based on numerical simulations and regression of test data, Lu *et al.* [8] proposed an effective FRP tensile strain at debonding.

Teng *et al.* [10] presented a smeared crack approach in finite element simulation of intermediate crack-induced debonding failure. A design model for limiting FRP tensile strain, based on interfacial stress distributions determined using finite element method and verified with database of experimental tests, has been proposed.

VERIFICATION OF CODE PROVISIONS AND PROPOSED MODELS

The allowable tensile strains ε_{fd} for FRP laminates evaluated by these models motioned above and their statistical results of the percentage ratios of the allowable-to-experimental tensile strain in FRP laminate at debonding, are listed in Table **3** and Table **4**. The validities of these models are summarized in Table **6**.

The maximum, minimum, and average percentage ratios evaluated by the ACI model are 364%, 79%, and 166%, respectively, the range of predictions ratios is 285% with coefficient of variation of 41%. For the fib-1 model, its evaluated maximum, minimum, and average ratios are 106%, 28%, and 52% respectively, and having the range of predictions ratios of 78% with coefficient of variation of 39%. However, for the fib-2 model, the maximum, minimum, and average ratios are 494%, 118%, and 232%, respectively, and having the range of predictions ratios of 376% with coefficient of variation of 40%. The average allowable-to-experimental ratio assesed by the CECS model is 176% with coefficient of variation 43%, and the range of the prediction ratios is 283%, respectively. The TR55 shows a similar overall performance to the fib-1model, and the average, the range, and the coefficient of variation of the prediction ratios evaluated by the TR55 model are 102%, 39%, and 66%, respectively. The maximum, minimum, and average ratios by the CNR DT200 are 239%, 57%, and 112%, respectively, and having the range of predictions ratios of 182% with coefficient of variation of 40%.

The maximum, minimum, and average ratios are 137%, 34%, and 64% evaluated by the Teng2003 model, respectively, and the range of predictions ratios is 103% with coefficient of variation of 40%. The maximum, minimum, and average ratios are 273%, 45%, and 94% asseded by the the Teng2004 model, respectively, the range of predictions

Table 6. Summary of Validities of Different Models for Evaluating Allowable Tensile Strains in FRP Laminates at Initial Debonding, (%)

Models	Max. ratio	Min. ratio	Average	Cov.
ACI 440	364	79	166	41
CECS146	393	111	176	43
JSCE	174	49	81	39
fib-1	106	28	52	39
fib-2	494	118	232	40
TR55	138	36	67	39
DT200	239	57	112	40
Teng2003	137	34	64	40
Said-Wu	300	77	136	45
Lu	347	59	130	50
Teng2004	273	45	94	55

ratio is 228%. According to the average ratio, this model seems suitable to evaluate the allowable tensile strain; however, the evaluated results of this model have the highest dispersion with coefficient of variation of 55%. The maximum, minimum, and average ratios are 347%, 59%, and 130% calculated by the Lu model, respectively. The range of predictions ratios is 289% with coefficient of variation of 50%. The average allowable-to-experimental ratio is 136% by the Wu model, and the range of prediction ratios is 223% with coefficient of variation 45%.

The statistical results show that all the predicted allowable tensile strains depict a great difference with the experimental results and have a high level of dispersion. Similar predictions of the maximum allowable strain to mitigate intermediate crack-induced debonding, were found in these models and provisions issued by ACI 440.2R-08, fib-2, DT200, and CECS146; and proposed by Said-Wu, Lu *et al*, and Teng2004. In all these cases, these proposed models provided non-conservative estimations of FRP tensile strain to cause debonding. These models highly overestimate the debonding tensile strains for FRP laminates. The JSCE, TR-55, fib-1 and Teng2003 provide very conservative estimations of allowable tensile strains for FRP laminates debonding.

CONCLUSIONS

Based on the results obtained from the current study, the following conclusions may be drawn:

1) All the allowable tensile strains of FRP laminates for preventing debonding failure evaluated by these proposed models exhibit a great difference with experimental results and have a high level of dispersion. Therefore, these models are not suitable to evaluate the allowable tensile strain in FRP laminates to mitigate debonding failure in FRP-strengthened RC beams.
2) Most of the models are basically developed by simply shear test results. As it is well known, the simply shear test cannot reflect all the factors affecting the debonding failure of FRP laminates in flexural FRP-strengthened RC members. This is why the predicted results are rather very conservative or very non-conservative, and have a high level of dispersion.
3) Intermediate crack-induced debonding failure is the dominant failure mode in flexurally FRP-strengthened RC members, more research should be done on this failure pattern to make better understanding of its mechanism and to ensure its safety of the strengthened members.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

ACKNOWLEDGEMENTS

None declared.

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