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Reliabilty-based Torsional Design of Reinforced Concrete Beams Strengthened with CFRP Laminate

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ABSTRACT

The structural reliability of torsional concrete beams strengthened with full and strip wrapping of carbon fiber reinforced polymer (CFRP) laminate is investigated. The first order-second moment reliability method has been applied to make a reliability assessment on the torsional capacity designed by technical guideline in Iran. The code No.345 published by the Management and Planning Organization of Iran (MPO 345-2006) is the first technical code in Iran for design of concrete members strengthened with CFRP laminate. In this work, the average reliability indexes for unstrengthened, strengthened with full wrap and strengthened with strip wrap beams have been found. The results indicate that the MPO design guideline are some unconservative. A reliability strengthening ratio is introduced for assessment of the variation in average reliability index before and after strengthening with different resistance factors. A parametric study on this factor reveals that if the reliability level of the strengthened reinforced concrete beams is kept to be consistent with their similar unstrengthened beams, a value of 0.89 and 0.81 for strengthened with full wrap and strengthened with strip wrap, should be applied, respectively.

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1. INTRODUCTION

Fiber-reinforced polymer (FRP) composite materials have been developed into economically and structurally viable construction materials for buildings and bridges over the last 25 years. They have been used in structural engineering in a variety of forms such as structural profiles, internal reinforcing bars for concrete members, strips and sheets for external strengthening of concrete and other structures. Externally bonded FRP composites are an increasingly adopted technology for the renewal of existing concrete structures [1-3]. For further use of such materials, a design code is needed that considers the inherent material variability of the FRP, as well as the variations introduced during field fabricate and environmental exposure while they are in service. There are several current guidelines for the use of FRP for strengthening reinforced concrete structures such as: ACI [4], ISIS [5] and FIB [6]. The first design guideline in Iran released in 2006, titled as "The Guideline for Design Specification of Strengthening RC Buildings Using Fiber Reinforced Polymers (MPO-345:2006)" [7]. The guidelines are all quite similar in their design approach, and at first glimpse all appear very similar to Load and Resistance Factor Design (LRFD) provisions. All use a limit states approach for defining design-checking equations. Design procedures and equations are given for basic strength limit states such as flexure, shear and torsion. However, the accuracy of these approaches is questionable in some cases, particularly in torsion. Thus, while these guidelines are a significant advance in the use of FRP for strengthening of concrete structures, there is still work to be done to develop a code in the preferred LRFD format.

In this regard, several studies have been performed for the reliability assessment of the reinforced concrete members strengthened with FRP which a number of them are mentioned in the following. The first study on the reliability of FRP-strengthened reinforced concrete members was conducted by Plevris et al. [8]. These authors recognized that deterministic methods for

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design of FRP-strengthening could not account for the statistical variation in the design variables. The study was conducted on reinforced concrete beams strengthened in flexure subjected to typical building loads. Resistance of strengthened members was characterized using Monte Carlo Simulation considering three modes of failure: steel yielding followed by CRFP rupture, steel yielding followed by concrete crushing and, for over-reinforced sections, catastrophic crushing of the concrete [8]. Reliability-based design of flexural strengthening was studied by Okeil, El-Tawil and Shahawy for reinforced concrete bridge girders and by El-Tawil and Okeil for prestressed bridge girders [9, 10]. Though these two studies considered different types of girders, they followed very similar procedures. Zheng et al. have presented reliability-based shear design for reinforced concrete beams with U-wrap FRP-strengthening. Their study provided a reliability assessment on the shear design provisions in the Chinese Technical code [11]. Wang et al. summarized some of the available tools and supporting databases that can be used to develop reliability-based guidelines for design and evaluation of FRP composites in civil construction [12]. Wieghaus and Atadero have investigated the effects of different levels of uncertainty in existing reinforced concrete structures and FRP materials on the reliability of repairs designed with ACI 440.2R-08 recommendations [13].

The main purpose of the present paper is to give a reliability evaluation of the torsional design provisions for CFRP-strengthened concrete beams according to the MPO guideline. The effects of some design variables on the reliability level are also assessed. Besides to the main scope, simplified method for calculating resistance factors is proposed.

2. DESIGN PROVISIONS

The ultimate torsional resistance of reinforced concrete beams with full or strip wrapping of CFRP laminate , T_U, consists of the resistance provided by CFRP laminate, T_{cfrp}, and that provided by reinforced concrete, T_S, as follows[7]:

$$T_U = T_{cfrp} + T_S \tag{1}$$

where, T_{cfrp} is obtained by the following relationship,

$$T_{cfrp} = 2bh \frac{t_{cfrp}\, w_{cfrp}}{s_{cfrp}} E_{cfrp}\, \varepsilon_{cfrpe} \tag{2}$$

where, b and h are the width and the height of the cross section, respectively, t_{cfrp} is the nominal thickness of one ply of CFRP laminate, w_{cfrp} is the width of CFRP strip, s_{cfrp} is the center-to-center distance between CFRP strips, E_{cfrp} is the elasticity modulus of CFRP laminate and ε_{cfrpe} is the effective strain of CFRP laminate which is defined as follows,

$$\varepsilon_{cfrpe} = \min\left\{0.004, \varepsilon_{cfrp} R_1\right\} \tag{3}$$

where, ε_{cfrp} is ultimate strain of CFRP laminate and R_1 is effective strain to ultimate strain ratio and is defined as follows,

$$R_1 = 0.8\lambda_1 \left[\frac{f_c^{2/3}}{\rho_{cfrp} E_{cfrp}}\right]^{\lambda_2} \tag{4}$$

in which, f_c is the compressive strength of the concrete, λ_1 and λ_2 are constants equal to 1.35 and 0.3 for CFRP laminate, respectively, and ρ_{cfrp} is the shear reinforcement ratio of CFRP laminate which can be obtained by the following equation,

$$\rho_{cfrp} = \frac{2t_{cfrp} w_{cfrp}}{b_w s_{cfrp}} \tag{5}$$

where, b_w is the width of the web. T_S is calculated by [14]:

$$T_S = 2\phi_S A_0 A_t \frac{f_{yv}}{s} \cot\theta \tag{6}$$

where, $\phi_S = 0.85$ is the partial safety factor of steel strength, A_0 is the cross sectional area bounded by the center line of the shear flow, A_t is the area of one leg of the transverse steel reinforcement (stirrup), f_{yv} is the yield strength of the transverse steel reinforcement, s is the spacing of the stirrups and θ is the angle of torsion crack direction with respect to the horizontal line.

3. RELIABILITY ANALYSIS

3. 1. Limit State Function

The basic relationship of safety checking criteria in probability-based limit state design codes is:

$$R \geq S \tag{7}$$

where, R is the resistance and S is the load effect. The resistance depends on the material properties and manufacture procedures. The predicted load effect depends on load models and analysis assumptions. The structure is safe if the resistance exceeds the load effect. Conversely, the limit state is exceeded and failure occurs when the resistance is less than the load effect.

Generally, the limit-state indicates the margin of safety between the resistance and the load effect of structures. The limit-state function can be defined as [12, 15]:

$$Z(R,S) = R - S \tag{8}$$

The torsional design of reinforced concrete beams strengthened with CFRP laminate is expressed by the following equation.

$$R_d \geq \gamma_0 S_d = \gamma_D S_D + \gamma_L S_L \tag{9}$$

where, R_d is the factored resistance, $\gamma_0 = 1$ is the load factor, S_d is the maximum of combination of factored dead and live load effects, S_D and S_L are the characteristic load effects caused by dead load and live load, respectively. $\gamma_D = 1.25$ is the partial safety factor of dead load and $\gamma_L = 1.5$ is the partial safety factor of live load. Unfortunately, statistical data of dead and live loads consistent with local conditions of Iran cannot be found in the literature; so, the data proposed in references [8, 16-19] are adopted in this study. The statistical properties including bias (the ratio of the mean of a random variable to its nominal value), coefficient of variation (C.O.V) and distribution type are summarized in Table 1.

The limit state functions, Z, for unstrengthened, strengthened with full wrap and strengthened with strip wrap beams including computational uncertainty are expressed by the following equations, respectively.

$$Z = R_d - \gamma_0 S_d = \Omega_u T_S - (\gamma_D S_D + \gamma_L S_L) = 0 \tag{10}$$

$$Z = R_d - \gamma_0 S_d = \Omega_{fw} T_u - (\gamma_D S_D + \gamma_L S_L) = 0 \tag{11}$$

$$Z = R_d - \gamma_0 S_d = \Omega_{sw} T_u - (\gamma_D S_D + \gamma_L S_L) = 0 \tag{12}$$

where, Ω_u, Ω_{fw} and Ω_{fs} are the computational uncertainty factors associated with analytical method for unstrengthened, strengthened with full wrap and strengthened with strip wrap beams, respectively. S_D and S_L are determined by [19]:

$$S_D = \frac{\gamma_0 S_d}{\gamma_D + \gamma_L \eta} \tag{13}$$

$$S_L = \frac{\eta(\gamma_0 S_d)}{\gamma_D + \gamma_L \eta} \tag{14}$$

in which, η is the load effect ratio ($\eta = \frac{S_L}{S_D}$). Obviously, the three factors Ω_u, Ω_{fw} and Ω_{fs} are random variables and are generally defined as follows,

$$\Omega = \frac{T^{\exp}}{T^{pre}} \tag{15}$$

where, $T^{\exp}$ is the torsional resistance of concrete beams obtained by experiment; T^{pre} is the predicted value from Equations (1) and (6). There are limited experimental studies on torsion strengthening of reinforced concrete beams using CFRP materials in the literature. The experimental data used herein are obtained from references, [20-25]. Common torsional strengthening configurations include full and strip wrapping along the entire beam, jacketing of three sides and, side bonding on two sides with or without anchorages. In this work, to assemble a consistent database, all beams selected of full and strip wrapping along the entire beam type. A total of 33 specimens (11 specimens for unstrengthened, 8 specimens for strengthened with full wrap and 14 specimens for strengthened with strip wrap beams) are collected to evaluate the statistics of Ω_u, Ω_{fw} and Ω_{fs}. As shown in Table 2, the statistical means of Ω_u, Ω_{fw} and Ω_{fs} are 1.07, 1.03 and 0.875, respectively.

TABLE 1. Statistical data of dead and live loads

Load pattern	Bias	Coefficient of variation	Probability distribution	Load factor[14]
Dead	1.05	0.1	Normal	1.25
Live	1	0.25	Extreme 1	1.5

TABLE 2. Statistics of the computational uncertainty factors

Reference	Ω_{fw}	Ω_{fs}	Ω_u
Ameli, Ronagh and Dux [20]	1.09	0.85	1.10
Ghobarah et al. [21]	1.07	0.837	1.08
Mohamadizadeh and Fadaee[22]	0.92	0.826	1.03
Panchacharam and Belarbi [23]	1.04	0.99	1.07
Hii and Al-Mahaidi [24]	-	0.9	1.08
Zhang et al. [25]	-	0.85	1.06
Average	1.03	0.875	1.07

3. 2. Analytical Methods

Different methods have been developed to calculate the reliability index [17]. In this work, the first order-second moment reliability method will be carried out to calculation. This method computes a reliability index β using a geometric interpretation of the minimum distance between the point corresponding to the mean values of the parameters used in the analysis (the peak point of the probability distribution function of the parameters) and an ultimate limit state surface. In this method, the limit state function is represented as the first-order Taylor series expansion at the mean value point. In the present work, FERUM software is used for doing such calculations.

3. 3. Random Variables Mohammadizadeh and Fadaee [22, 26] performed experimental studies on CFRP strengthened reinforced concrete beams under torsion [Figure 1]. The value of random variables is adopted from their work, [22]. The reliability analysis of the unstrengthened and strengthened beams by Equations (1) and (6) requires probabilistic models of the important engineering variables and supporting databases to characterize the uncertainties of such variables. These statistical data should be representative of values that would be expected in a structure and should reflect uncertainties due to inherent variability, modeling and prediction, and measurement. In this work, eight independent random variables, i.e. width and height of the cross section, area of one leg of the transverse steel reinforcement (stirrup), yield strength of the transverse steel reinforcement, spacing of the stirrups, elasticity modulus of CFRP, the center-to-center distance between CFRP strips and the width of CFRP strips have been included. A literature review was carried out to select the proper statistical characteristics for each random variable [11, 13, 27, 28]. The statistical properties including bias, coefficient of variation (C.O.V) and distribution type of the random variables are summarized in Table 3.

3. 4. Reliability Index FERUM software has been applied to calculate reliability index, β. Reliability indexes were calculated for different load effect ratios ($\eta = \frac{S_L}{S_D}$), i.e., 0.1, 0.5, 1, 1.5, 2, 2.5. Averaging all reliability indexes gives the global average reliability indexes of 3.64, 3.38 and 3.17 for unstrengthened, strengthened with full wrap and strengthened with strip wrap beam, respectively.

TABLE 3. Statistics of random variables

Random variables	Nominal value	Bias	C.O.V	Probability distribution
b(mm)	150	1	0.03	Normal [13]
h(mm)	350	1	0.03	Normal [13]
$A_t(mm^2)$	25.12	١	0.025	Normal [28]
$f_{yv}(MPa)$	480	1.281	0.0743	Normal [11]
s(mm)	80	1	0.06	Normal Assumed for this study
$E_{cfrp}(MPa)$	240000	1.04	0.06	Normal [11]
$S_{cfrp}(MPa)$	200	1	0.02	Normal [29]
$w_{cfrp}(MPa)$	100	1	0.02	Normal [11]

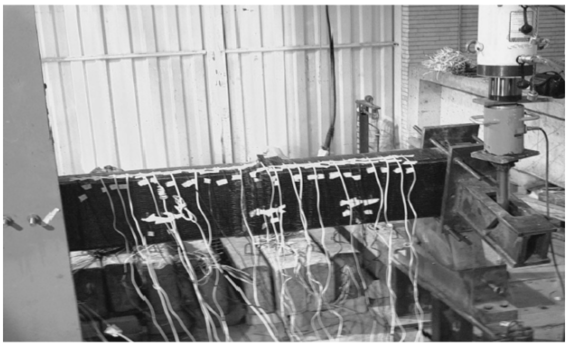

Figure 1. Test setup

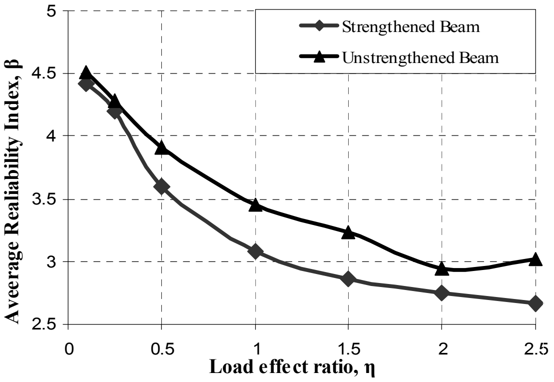

Figure 2. Load Effect Ratio for strengthened beam with full wrap

3. 5. Load Effect Ratio (η) Load effect ratio, η , has a significant influence on reliability level, as shown in Figures 2 and 3. As strengthened beams in Iranian guideline, if η increases from 0.10 to 2.5, the average index, β, decreases slightly. Figure 2 indicates, for any live load pattern, the average reliability index decreases as η increases but at a slowing rate. An increase in η from 0.1 to 2.5 can cause a 3% to15% decrease in reliability index of strengthened beams with full wrap. As it can be seen in Figure 3, β decreases slightly for η from 0.10 to 2 and increases slightly for η from 2 to 2.5. Due to the different statistics of live loads, the index, β, corresponding to unstrengthened beam is bigger than that corresponding to strengthened beam with strip wrap. The result indicates that β decreases almost 11% to 24% for strengthened beam with strip wrap with respect to the unstrengthened beam.

3. 6. Parametric Study The effect of each design variable on the reliability level is investigated by sensitivity analyze. All computational results are illustrated in Figures 4 and 5 by histograms. For the strengthened beam with full wrap elasticity modulus of

CFRP laminate, E_{cfrp}, plays a major role in the reliability level (Figure 4). To make a further investigation on the effect of E_{cfrp}, eight elasticity modulus of CFRP laminate were selected. The result shown, as E_{cfrp} increases, the average reliability index increases monotonically but at a slowing rate. As E_{cfrp} increases from 210 GPa to 480 GPa, the average reliability index increases 9% see (Figure 6). As shown in Figure 5, yield strength of the stirrups, f_{yv}, is the dominant influencing factor. The effects of other design variables are appeared to be insignificant on the reliability level. Design variable f_{yv} is then selected for conducting a detailed parametric study of its effect on the reliability level, as shown in Figure 7. Five strength values for the stirrup, i.e. f_{yv}=240, 300, 360, 420 and 480 MPa were selected. As f_{yv} increases from 240 Mpa to 480 Mpa, an increase of 5% in average reliability index can be obtained for both types of the beams.

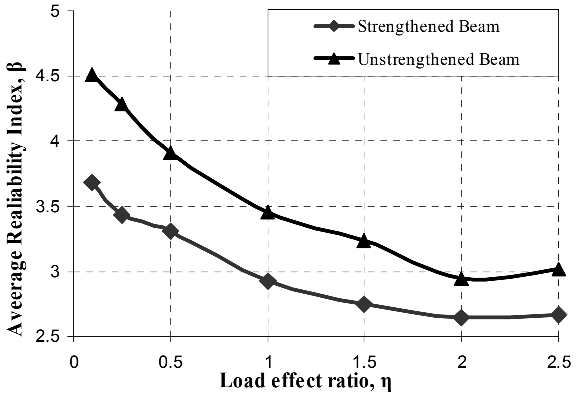

Figure 3. Load Effect Ratio for strengthened beam with strip wrap

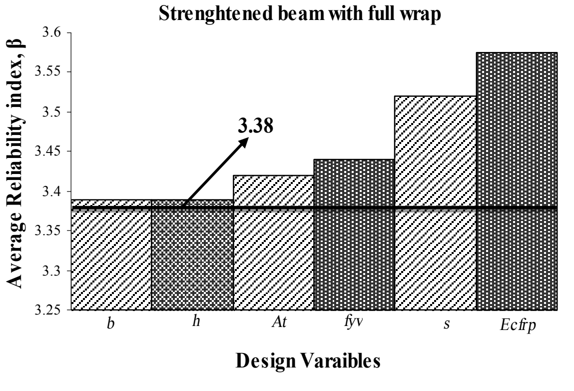

Figure 4. Effects of design variables on average reliability index for the strengthened beam with full wrap

3. 7. Resistance Reduction Factor

For the purpose of making a further study on the resistance factor from the probabilistic point of view, two reliability strengthening ratios, δ_1 and δ_2, are defined as,

$$\delta_1 = \frac{\beta_{fw}}{\beta_u} \tag{16}$$

$$\delta_2 = \frac{\beta_{sw}}{\beta_u} \tag{17}$$

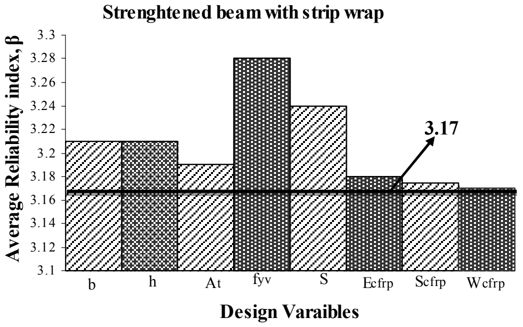

Figure 5. Effects of design variables on average reliability index for the strengthened beam with strip wrap

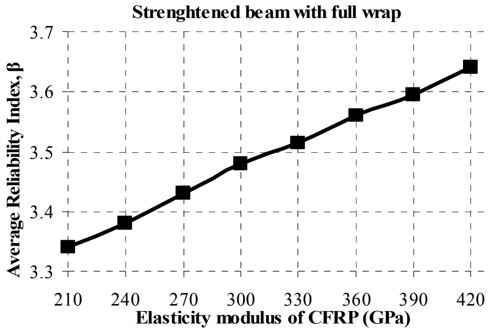

Figure 6. Effect of elasticity modulus of CFRP laminate on average reliability index

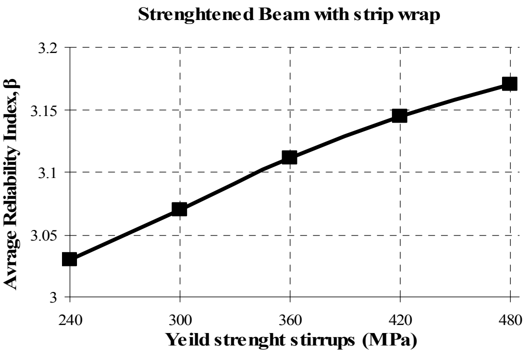

Figure 7. Effect of yield strength of the stirrups on average reliability index

where, β_{fw}, β_{sw} and β_u are the average reliability indexes of beams strengthened with full and strip wrapping and unstrengthened, respectively. β_u is calculated by averaging reliability indexes for different live load patterns. β_{fw} and β_{sw} are ϕ-dependent. For each value of ϕ, the corresponding computational uncertainty factors (see Table 4), Ω_{fw} and Ω_{fs}, are applied to calculate all reliability indexes of strengthened concrete beams for each live load pattern. Averaging such indexes reaches to β_{fw} and β_{sw}.

A linear regression is shown in Figures 8 and 9. If we would like to maintain the consistency of reliability level before and after strengthening, we may set δ_1 and δ_2, equal to 1.0 and the corresponding resistance factor would turn out to be 0.89 and 0.81 for beams strengthened with full and strip wrapping, respectively. For achieving a higher reliability level or a lower reliability level after strengthening, a resistance factor smaller or greater than 0.89 or 0.81 must be applied, as determined by the following equations,

$$\delta_1 = -1.36\phi + 2.21 \tag{18}$$

$$\delta_2 = -0.68\phi + 1.551 \tag{19}$$

TABLE 4. Summary of the Statistics of the computational uncertainty factors Ω_{fw} and Ω_{fs}

ϕ	0.8	0.85	0.9	0.95	1
Ω_{fw}	1.17	1.13	1.1	1.06	1.03
Ω_{sw}	1.22	1.16	1.096	1.04	0.99

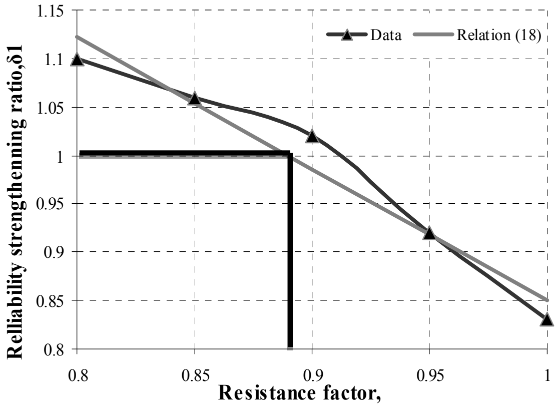

Figure 8. Relationship between reliability strengthening ratio and resistance factor for the strengthened beam with full wrap

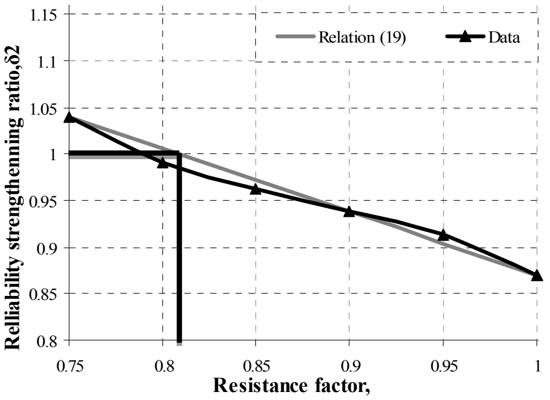

Figure 9. Relationship between reliability strengthening ratio and resistance factor for the strengthened beam with strip wrap

4. CONCLUSIONS

The purpose of this paper is to assess the reliability of the torsional design provisions for CFRP strengthened concrete beams according to the MPO guideline. Some conclusions can be drawn as follows through such assessment.

1. It is concluded that global average reliability indexes for unstrengthened beam, strengthened beam with full wrap and strengthened beam with strip wrap are 3.61, 3.38 and 3.17, respectively. Therefore, design provisions in the MPO guideline seems to be unconservative to some extent.
2. Load effect ratio, η, has a significant influence on the reliability level for both type of the strengthened beams. The effect of η on reliability level for the strengthened beam with strip wrap is even more remarkable. The results indicate that the average reliability indexes, β, decreases about 11% to 24 % for strengthened beam with strip wrap comparing to unstrengthened beam.
3. Elasticity modulus of CFRP laminate, E_{cfrp} and yield strength of stirrups, f_{yv}, are dominant influencing factors among all the design variables for beams strengthened with full and strip wrapping, respectively. As E_{cfrp} increases from 210 GPa to 420 GPa, the average reliability index increases 9%. In addition, while the yield strength of stirrups , f_{yv}, increases from 240 MPa to 480 MPa, the average reliability index increases 5%.
4. Application of the resistance factor $\phi = 1$ for full and strip wrapping suggested in the code could lead to a significant decrease in reliability level after strengthening. A relationship between δ_1, δ_2 and ϕ obtained from the linear regression of the parametric

study shows that ϕ could be taken as 0.89 and 0.81 for keeping the consistency in reliability level before and after CFRP torsional strengthening with full and strip wrapping, respectively. For simplicity, in design practice, ϕ = 0.85 and 0.8 are suggested to be used.

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Reliabilty-based Torsional Design of Reinforced Concrete Beams Strengthened with CFRP Laminate

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چکیده

در این مقاله قابلیت اطمینان سازه ای تیرهای بتن آرمه تقویت شده با پلیمرهای مسلح شده با الیاف کربن(CFRP) به صورت دورپیچ کامل و نواری تحت اثر پیچش بررسی شده است. برای ارزیابی قابلیت اطمینان ظرفیت پیچشی، طراحی بر اساس راهنمای طراحی ایران انجام و سپس روش قابلیت اطمینان مرتبه اول- لنگر دوم بکار برده شده است. اولین آیین نامه برای طراحی اعضای بتن آرمه تقویت شده با CFRP در ایران، نشریه شماره ٣٤٥ سازمان مدیریت و برنامه ریزی کشور (MPO 345-2006) می باشد. در تحقیق حاضر، میانگین شاخص قابلیت اطمینان برای تیرهای تقویت نشده و تیرهای تقویت شده با دورپیچ کامل و نواری بدست آمده است. نتایج نشان میدهد که راهنمای طراحی MPO تاحدی غیر محافظه کارانه است. برای ارزیابی تغییرات میانگین شاخص قابلیت اطمینان قبل و بعد از مقاوم سازی با ضرایب مقاومت مختلف، یک نسبت مقاومت ایمن معرفی شده است. مطالعه پارامتری این ضریب نشان میدهد که اگر تراز قابلیت اطمینان تیرهای بتن آرمه تقویت شده با تیرهای بتن آرمه مشابه تقویت نشده ثابت نگه داشته شود بایستی به ترتیب مقدار ٠.٨٩ و ٠.٨١ به عنوان ضریب مقاومت برای تیرهای تقویت شده با دورپیچ کامل ونواری بکار برده شود.

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