RELIABILITY ASSESSMENT ON FLEXURAL DESIGN OF FRP-RC BEAMS TAKING INTO ACCOUNT EARTHQUAKE LOAD COMBINATIONS

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Corrosion and magnetic inconsistency of steel reinforced concrete (Steel-RC) cause deficiency of it in some environments. For that reason, the fiber reinforced polymer (FRP) by providing a combination of non-corrosive and non-magnetic properties, is considered as a perfect replacement instead of steel. But the FRP bars represent different mechanical properties from steel bars like high tensile strength, low elasticity modulus and brittle ultimate behavior. Thereby, the Steel-RC provisions should be modified to reach a suitable design specific to FRP reinforced concrete (FRP-RC) and then, a probabilistic assessment is required to clarify how much the new modifications are reliable.

In this study, the reliability of flexural design of FRP-RC beams recommended by ACI 440.1R-06 code is assessed by an optimization technique and the results are compared with the Steel-RC beams designed according to ACI 318 especially with regard to earthquake load effects.

The reliability index β is the minimum distance from the origin to limit state function (LSF) in the normalized space (Nowak and Collins, 2000). Therefore, from an optimization point of view, the genetic algorithm optimization (GA) is able to calculate β as a technique to minimize that distance. Additional details about the GA are given in the full paper.

Two flexural failure modes are reported for FRP-RC beams: FRP rupture and concrete crushing. When the longitudinal reinforcement ratio of FRP-RC beams is less than the balanced reinforcement ratio $\left(\rho_f \leq \rho_{Bal}\right)$, FRP rupture failure mode occurs and Eq. (1) expresses the LSF of this mode:

$$LSF_{FRP} = \xi_{FRP}\, \rho_f\, f_{fu}\left(1 - 0.5\beta_1 \frac{E_f \varepsilon_{cu}}{E_f \varepsilon_{cu} + f_{fu}}\right) b d^2 - M_{Dead} - M_{Live} - M_{Earth} \qquad (1)$$

But when the longitudinal reinforcement ratio is more than the balanced reinforcement ratio $\left(\rho_f > \rho_{Bal}\right)$, beam fails in concrete crushing mode and the LSF of this failure mode is:

$$LSF_{con} = \xi_{con}\, \rho_f f_f \left(1 - 0.59 \frac{\rho_f f_f}{f_c'}\right) b d^2 - M_{Dead} - M_{Live} - M_{Earth} \qquad (2)$$

Where in the above equations ξ_{FRP} and ξ_{con} are the computational uncertainty factors that are the ratios of the experimental value to the value predicted by ACI 440 and the subscripts represent each mode of failure. The f_{fu}, E_f, f_f, f_c', ε_{cu}, b, d and β_1 are the tensile strength, elasticity modulus, stress level in the FRP bars, compression strength and ultimate strain of concrete, width and effective depth of beam and the factor relating depth of equivalent rectangular compressive stress block to neutral axis depth, respectively. The M_{Dead}, M_{Live} and M_{Earth} are the dead, live and earthquake load effects respectively. If one of the live or earthquake loads does not exist in the proposed load combination, it is eliminated from the LSFs. In this study, the following load combinations are considered: $1.2D + 1.6L$, $1.2D + 1.0L + 1.0E$ and $0.9D + 1.0E$.

In line with the ACI 318 trend of reliability for steel-RC beams, herein the reliability index β of 3.5 and 4 for FRP-RC beams are assumed for $1.2D + 1.6L$ load combination (Szerszen and Nowak, 2003). It should be noticed that both flexural failure modes of FRP-RC beams behave in a brittle manner, but FRP rupture mode is more brittle than concrete crushing. Therefore, the FRP rupture requires a higher reliability level as compared to concrete crushing. To this aim, it can be assumed that the target reliability index β_T for FRP rupture and concrete crushing modes can be considered about 4 and 3.5 respectively for the gravity load combination (He and Qiu, 2011). However, for earthquake load combination, a lower reliability index is allowed since some level of damage can be expected in the event of earthquake. That means β_T for the earthquake load combinations can be taken less than that for the other load combinations (Nowak and Collins, 2000). Hence, the values of 2.5 and 3 for concrete crushing and FRP rupture modes seem to be appropriate values for target reliability for earthquake load combinations. Table 1 presents β calculated based on the reduction factors recommended by ACI 440 flexural design of FRP-RC beams. On the other hand, the reduction factors Φ are herein calculated so that the resulting reliability becomes equal to the target reliability (i.e. β_T) used in ACI 318 as listed in Table 1. From Table 1 it can be concluded that the reduction factors suggested by ACI 440 design provisions are more conservative than those of ACI 318 code.

Table 1. Reliability index β for each load combinations

Load Combination	Failure Mode	β	β_T	Φ
$1.2D + 1.6L$	FRP Rupture	6.05	4.0	0.87
	Concrete Crushing	4.73	3.5	0.84
$1.2D + 1.0L + 1.0E$	FRP Rupture	5.29	3.0	0.88
	Concrete Crushing	3.88	2.5	0.87
$0.9D + 1.0E$	FRP Rupture	4.04	3.0	0.71
	Concrete Crushing	2.86	2.5	0.71

Figure 1 Shows the calculated β for different values of strength reduction factors Φ for all three load combinations and for both failure modes. Based on Table 1 and Figure 1, it is concluded that the reduction factor $\Phi = 0.71$ for flexural design of FRP-RC beams yields a reliability level compatible with the traditional design of reinforced concrete.

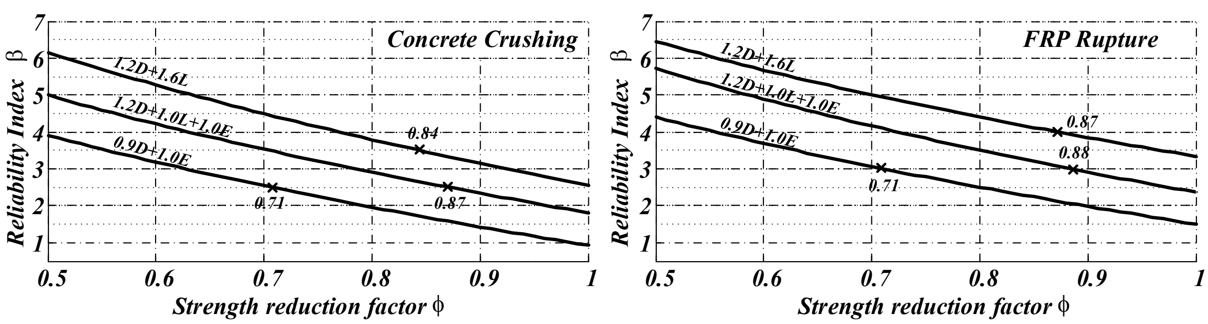

Figure 1. Reliability index β v.s reduction factor Φ for each failure mode

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