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Assessment of reliability-based FRP reinforcement ratio for concrete structures with recycled coarse aggregate

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Abstract. The present study assessed the reliability-based reinforcement ratio of FRP reinforced concrete structure applying recycled coarse aggregate (RCA) concrete. The statistical characteristics of FRP bars and RCA concrete were investigated from the previous literatures and the mean value and standard deviation were employed for the reliability analysis. The statistics can be regarded as the material uncertainty for configuring the probability distribution model. The target bridge structure is the railway bridge with double T-beam section. The replacement ratios of RCA were 0%, 30%, 50%, and 100%. From the probability distribution analysis, the reliability-based reinforcement ratios of FRP bars were assessed with four cases according to the replacement ratio of RCA. The reinforcement ratio of FRP bars at RCA 100% showed about 17.3% higher than the RCA 0%, where the compressive strength at RCA 100% decreased up to 27.5% than RCA 0%. It was found that the decreased effect of the compressive strength of RCA concrete could be compensated with increase of the reinforcement ratio of FRP bars. This relationship obtained by the reliability analysis can be utilized as a useful information in structural design for FRP bar reinforced concrete structures applying RCA concrete.

Keywords: reliability-based reinforcement ratio; FRP bars; recycled coarse aggregate (RCA); replacement ratio of RCA; structural design

1. Introduction

The importance of sustainable concrete development was addressed to preserve the limited resources for the needs of future generations of life on the earth (World commission on environmental and development 1987). Based on the above statement, concrete construction industry is advancing for requiring the sustainable concrete development. There are two significant research trends, thus, stronger durable and recycled materials. By using these materials, the service life of existing reinforced concrete (RC) can be extended or it is possible that CO_2 emission from production of cement is reduced. Therefore, the amount of natural resources in concrete construction can be consistently saved to realize the sustainable concrete development. With this reason, the use of two sustainable construction materials, i.e., FRP bars and recycled aggregate (RA) concrete, are going to be issued in future construction industry.

FRP bars is known as superior reinforcement to reinforced concrete due to high tensile strength and strong durability with non-corrosive property. There are many of researches about the structural performance of FRP reinforced concrete structures about flexure and serviceability (El-Nemr *et al.* 2018, Ju *et al.* 2017, Qin *et al.* 2017, Maranan *et al.* 2015), shear (Abdul-Salam *et al.* 2016, Pantelides *et al.* 2012, Ahmed *et al.* 2010), bond (Li *et al.* 2018, Wambeke and Shield 2006). These researches showed that FRP bars had good potential advantages as the structural reinforcement. Furthermore, the application on the real scale concrete slabs (Ju *et al.* 2018, Bouguerra *et al.* 2011) has reported that the structural performance is good enough with respective to the strength and serviceability as compared with steel reinforced concrete slabs. For the structural design, it has been conducted based on the strength design method using more conservative factors about the types of FRP materials and strength reduction, as compared the steel reinforced concrete structures. This design approach for FRP bars may be uneconomical with respective to the expense of FRP bars as compared to that of steel bar.

Another sustainable construction material is recycled aggregate concrete (RAC). As the natural aggregates has gradually been depleted, the importance of recycled concrete aggregate has been widely issued. Many of researches about RAC have been reported, i.e., compressive strength (Kurda *et al.* 2018, Deng *et al.* 2018, Arioglu *et al.* 2006), tensile strength (Silva *et al.* 2015, Zain *et al.* 2002), mixing improvement (Montero and Laserna 2017, Tam *et al.* 2006), structural capacity (Seara-Paz *et al.* 2018, Schubert *et al.* 2012) as well as fatigue (Arora and Singh 2016). These researches showed the feasibility of the use of RAC as the structural concrete. However, there are still uncertain aspects when the structural engineer designs the RAC members, i.e., lower quality than natural aggregate, uncertainty in field application, and negative understanding in the use of RAC. Nevertheless, RAC members must be

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main issue for sustainable concrete development in future. For design of RAC members, there is no specific design recommendation except the limitation of material property when RAC is used for structural members (Korea Construction Specification 2016).

Accordingly, based on the material uncertainty in structural design for FRP bar and recycled concrete aggregate, a proper design methodology is needed for extensive use of these structural materials.

In this study, the reliability-based reinforcement ratio of FRP reinforced concrete structure applying recycled coarse aggregate (RCA) concrete is assessed. For this, statistical data of FRP bars and RCA was investigated and summarized from the previous literature. The probability distribution with random variables were generated by Monte Carlo Simulation (MCS) and reliability analysis was done by the limit state function. The target bridge structure was selected with a railway bridge in the reason of highly vibrating structures by mass loads resulting in accelerating the structural damage. The reliability-based reinforcement ratios of FRP bars of the bridge applying FRP bars and RCA were investigated at the probability of failure corresponding to the reliability index of β = 3.5 (AASHTO2014) for the replacement ratio of RCA with 0%, 30%, 50%, and 100%, respectively.

2. Limit state function and reliability index

The reliability theory has already been used in various fields of engineering and is being used for analysis related with the safety of structures in civil engineering. The reliability analysis of the structure for safety is to estimate the probability of failure. In general, the failure of structures can be defined when a member stress exceeds the allowable stress. For reliability analysis, a specific limit state function should be formulated.

2.1 Limit state function (G)

The limit state function in safety of structure is configured by the limit state of the relationship between applied load and the resistance. In other words, since the limit state is the boundary state in failure of structure, it is a safe state when the limit state function is positive. For example, if there are the total load effect acting on the member (Q) and the strength of the member (or resistance, R), the limiting state function G can be defined as follows.

$$G(X_1, X_2, \dots, X_n) = R - Q > 0 \rightarrow R > Q \qquad \text{Safe}$$

$$G(X_1, X_2, \dots, X_n) = R - Q < 0 \rightarrow R < Q \qquad \text{Failure}$$

$$G(X_1, X_2, \dots, X_n) = R - Q = 0 \rightarrow R = Q \qquad \text{Limit state}$$

2.2 Reliability index

For the member resistance (R) and the external load (Q), the mean (μ) and standard deviation (σ) of the marginal state function are given by Eq. (1) and (2).

Table 1 Tensile property of GFRP bar

Bar type	Average tensile strength (MPa)	Coefficient of variation (COV) (%)	Modulus of elasticity (GPa)	Distribution type
GFRP bar	810	5	45.0	Lognormal

$$\mu_G = \mu_R - \mu_Q \tag{1}$$

$$\sigma_G = \sqrt{\sigma_R^2 \mp \sigma_Q^2} \tag{2}$$

The probability of failure is equal to the area of the probability density function of the critical state function in the region less than zero. The equation is introduced in Eq. (3).

$$P_F = P_r[G < 0] = \int_{-\infty}^{0} f_G(x)dx = \Phi\left(-\frac{\mu_G}{\sigma_G}\right) = \Phi(-\beta) \tag{3}$$

Where Φ is the cumulative distribution function of the standard normal distribution and β is the value called the reliability index, divided by the standard deviation. Finally, the reliability index is calculated as following Eq. (4).

$$\beta = \frac{\mu_G}{\sigma_G} = \frac{\mu_R - \mu_Q}{\sqrt{\sigma_R^2 + \sigma_Q^2}} \tag{4}$$

3. Statistics for FRP bar and recycled aggregate concrete

3.1 GFRP bar

FRP bar is a non-homogeneous reinforcement in contrast of the steel bar so that the mechanical property, i.e., the tensile strength, is significantly affected by the fiber volume fraction and alignment, the matrix types around the fibers, the manufacturing conditions. The statistical value for generating random variable of FRP bar in probability distribution analysis was employed by the literature (Pilakoutas *et al.* 2002) and it was exhibited in Table 1. The type of probability distribution was considered lognormal distribution.

3.2 Recycled coarse aggregate concrete

The statistical information of the concrete according to the replacement ratio of RCA were obtained from previous literatures (Ajdukiewicz and Kliszczewicz 2002, Choi *et al.* 2007, Corinaldesi 2010, Duan and Poon 2014, Jeon *et al.* 2009, Keum *et al.* 2011, Kwan *et al.* 2012, Lee *et al.* 2015, Malesev *et al.* 2010, Medina *et al.* 2014, Poon *et al.* 2004, Rahal 2007, Rao *et al.* 2011, Sim and Park 2011, Tsoumani *et al.* 2014, Xiao *et al.* 2005, Yang and Jeong 2016). The replacement ratios of RCA were classified as 0%, 30%, 50%, 100%. The average compressive strength and standard deviation were statistically calculated and summarized in

Table 2 Summary of statistics of compressive strength of concrete from the literatures

Replacement ratio (%)	Average compressive strength (MPa)	Standard deviation (MPa)	COV (%)
0	46.1	8.0	17
30	39.7	6.3	16
50	37.7	6.0	15
100	33.4	6.4	19

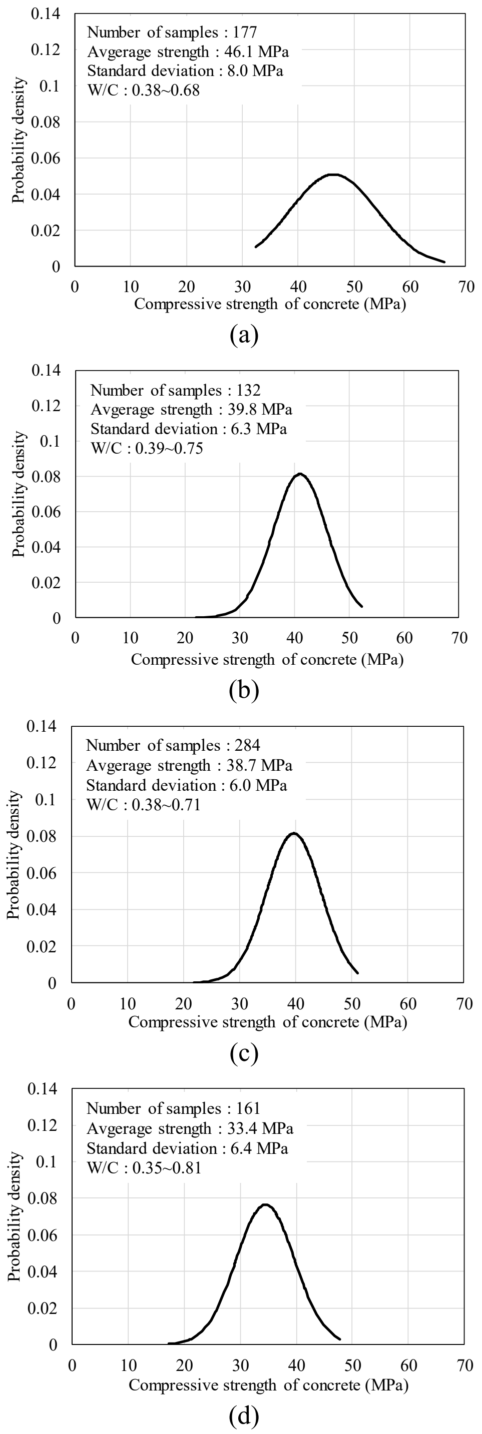

Fig. 1 Lognormal distributions of statistics compressive strength of concrete according to the replacement ratio of RCA; (a) 0%, (b) 30%, (c) 50%, and (d) 100%

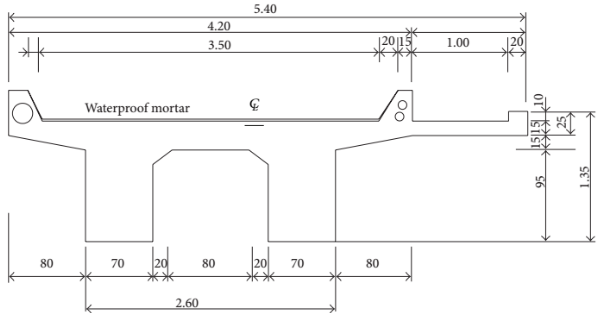

Fig. 2 The target bridge in this study (Ju *et al.* 2014)

Table 3 Statstics for load effect to the target bridge (Ju *et al.* 2014)

	Mean[a]	Mean/Nominal	COV	Load factor	Probability distribution
Dead load	180.0 kNm	1.05	0.1	1.4	Normal
Live load	580.1 kNm	1.00	0.2-0.4	2.0	Lognormal

[a]obtained from finite element analysis

Table 2. Note that the standard deviation of the compressive strength were almost same, where the average compressive strength decreased with the increase of the replacement ratio of RCA. Normal distributions of the compressive strength of concrete were introduced in Fig. 1.

4. Reliability analysis

In order to perform the reliability analysis, the limit state function should be defined in advance. The function is consisted of the external load effect and the resistance effect. Then, the probability of failure between the external load effect and the resistance effect based on the probability distribution is calculated. The reliability-based reinforcement ratio is finally calculated corresponding to the design target reliability index of 3.5.

4.1 External moment effect by design load for the target bridge

The target bridge structure to investigate the reliability-based reinforcement ratio applying FRP bars and RCA concrete is a simply supported railway concrete bridge in Korea introduced in Fig. 2. The external moment effect (Q) due to the live load and the live load considering the load factor acting on the concrete beam can be expressed in Eq. (5). The external moment of the target bridge was obtained by finite element analysis with the specified design load combinations. The analysis result was summarized in Table 3.

$$M_Q = M_{dead} + M_{live} \tag{5}$$

where,
M_{dead} = dead load effect in flexural moment
M_{live} = design load effect in flexural moment

Table 4 Input parameters for probability distribution analysis

Classifications		Mean value	Standard deviation	Probability distribution
f_c'	RCA0%	46.1 MPa	7.98 MPa	Normal
	RCA30%	39.7 MPa	6.27 MPa	Normal
	RCA50%	38.7 MPa	5.96 MPa	Normal
	RCA100%	33.4 MPa	6.36 MPa	Normal
f_f		810 MPa	40.5 MPa	Lognormal
b		1,900 mm	Determinant	-
d		1,250 mm	Determinant	-
h		1,200 mm	Determinant	-

4.2 Moment resistance effect

When a concrete structure is reinforced with FRP bars, ACI 440-15 (2015) allows both the tension and compression control in the design of flexural members reinforced with FRP bars. In order to guarantee the marginal safety in failure, it is recommended that the concrete structures should be designed in concrete crushing manner (Nanni *et al.* 1993). This is because the structures have to contain the sufficient safety from the brittle failure of FRP bars which is governed in elastic behavior until failure. In this case, the nominal moment resistance (M_R) is defined by using Eq. (6). For probability distribution analysis, input parameters were summarized in Table 4. Among the parameters, the compressive strength of concrete and the tensile strength of FRP bar were considered variables.

$$M_R = \rho_f f_f \left(1 - 0.59\frac{\rho_f f_f}{f_c'}\right) bd^2 \tag{6}$$

where,

ρ_f = reinforcement ratio of tensile reinforcement

f_f = stress in FRP reinforcement in tension $\left(\sqrt{\frac{(E_f \varepsilon_{cu})^2}{4} + \frac{0.85\beta_1 f_c'}{\rho_f} E_f \varepsilon_{cu}} - 0.5E_f \varepsilon_{cu}\right) \le f_{fu}$

f_c' = compressive strength of concrete (MPa)

b = width of cross section (mm)

d = effective depth from the top fiber of compressive zone (mm)

E_f = modulus of elasticity of concrete (MPa)

ε_{cu} = ultimate strain of concrete (0.003)

β_1 = concrete strength reduction factor continuously from 0.85 to 0.65

f_{fu} = design tensile strength of FRP with environmental reduction factor (MPa)

4.3 Configuration of limit state function

The limit state function, G, can be expressed as Eq. (7) by the equation for external load effect considering the load factor and the moment resistance.

$$G = R - Q \tag{7}$$

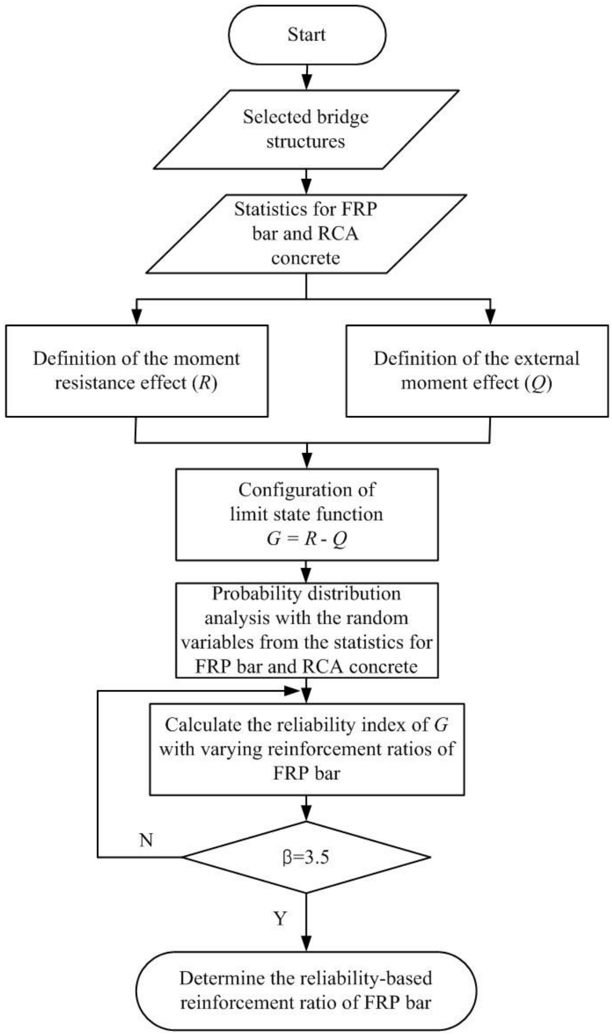

Fig. 3 The process of reliability analysis

4.4 Reliability analysis process

Reliability analysis for obtaining the reinforcement ratio of FRP bar for the target bridge applying using RCA concrete is processed as follows: i) Check the geometry of the target bridge. Effective design section is determined based on the force equilibrium condition. ii) Statistics are summarized for FRP bar and RCA concrete from the literature reviews. There are average and standard deviation of tensile strength for FRP bar and the compressive strength of RCA concrete. iii) The moment resistance function (M_n) is configured based on the cross sectional design equation for reinforced concrete T-beam. iv) Probability distribution for resistance (R) and external force (Q) is obtained with random variables by using Monte Carlo Simulation (MCS). v) The limit state function, $G = R - Q$, is configured. The Q is fixed property from the finite element analysis for the target bridge and R is variable property according to the reinforcement ratio of FRP bar. vi) Reliability analysis is performed. The reinforcement ratio of FRP bar varies within the designated range and the reliability index of the limit state function is investigated. vii) Linear interpolation between the reinforcement ratio of FRP bar and the corresponding reliability index is performed and the

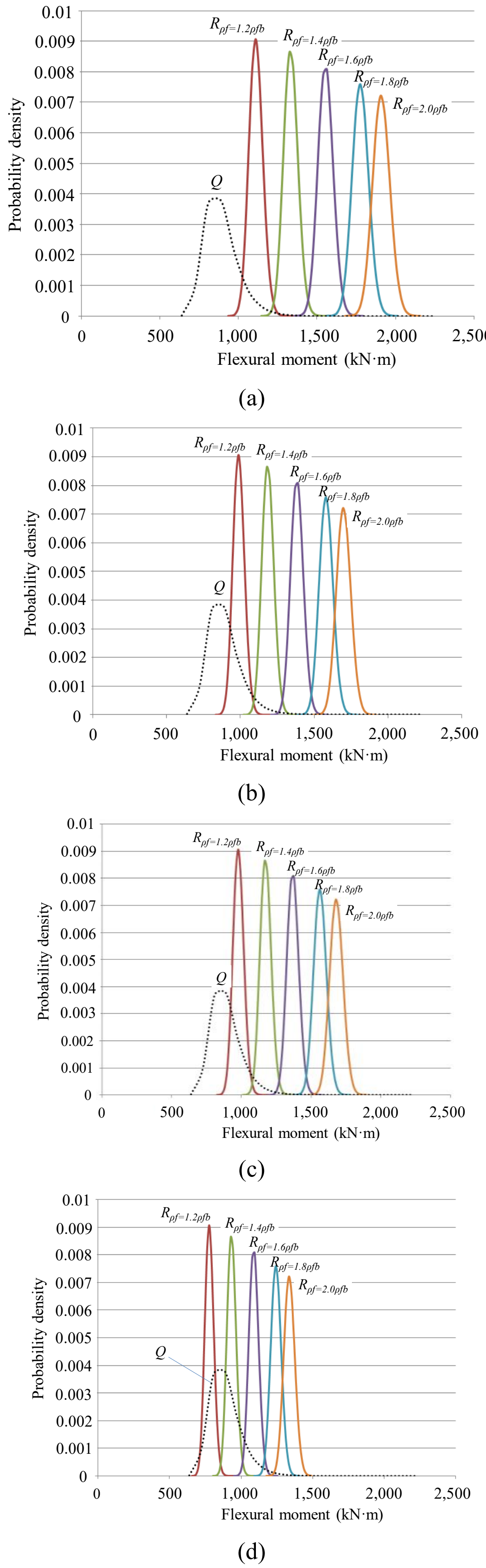

Fig. 4 Probability distribution analysis for Q and R with the designated reinforcement ratios of FRP bars according to the replacement ratio of RCA; (a) 0%, (b) 30%, (c) 50%, and (d) 100%

Table 5 The results of reliability-based reinforcement ratio

Replacement ratio of RCA (%)	Reinforcement ratio (ρ_f)
0	0.00797
30	0.00867
50	0.00883
100	0.00934

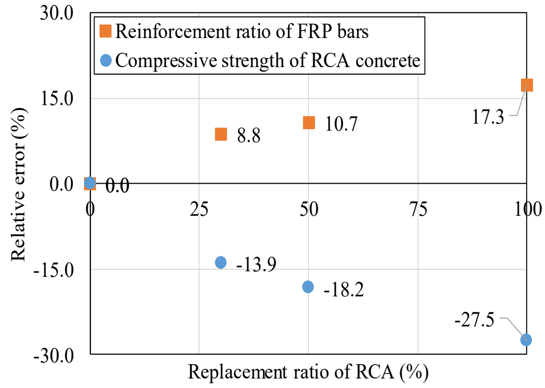

Fig. 5 Comparison between the compressive strength of RCA concrete and the reinforcement ratio of FRP bars

FRP bar and the corresponding reliability index is performed and the reinforcement ratio of FRP bar is obtained corresponding to the reliability index of 3.5.

5. Reliability-based reinforcement ratio of FRP bars

5.1 Probability distribution analysis

Probability distribution analysis provides how much the area between the external moment and the moment resistance is overlapped. The superposed area is defined as the probability of failure. Fig. 4 shows the probability distribution analysis results according to the four types of replacement ratio of RCA. Note that the probability of failure decreased with the increase of the reinforcement ratio of FRP bar. Because the compressive strength of RCA concrete decrease with the increase of the replacement ratio of RCA, the probability distributions of the moment resistance are moved toward the external moment distribution as the replacement ratio of RCA increased up to 100%. Accordingly, the probability of failure increases, where the reliability index decreases.

The reliability index is obtained from the probability of failure. The reliability analysis is iterated until the reinforcement ratio corresponding to the target reliability index of 3.5 is obtained. Thus, the reliability-based reinforcement ratios of FRP bars are calculated according to the replacement ratios of RCA.

In order to determine the reinforcement ratio (ρ_f) corresponding to the reliability index of $\beta = 3.5$, the parametric study was done by using five different reinforcement ratios of FRP bars with $1.2\rho_{fb}$, $1.4\rho_{fb}$, $1.8\rho_{fb}$, $2.2\rho_{fb}$, and $2.6\rho_{fb}$, where ρ_{fb} is the balanced reinforcement ratio of FRP reinforced flexure section in compliance with ACI 440 1R-15. Fig. 3 shows the entire analysis process for the reliability-based reinforcement ratio for the target bridge structure applying FRP bar and RCA concrete. The balanced reinforcement ratio of FRP bars is introduced in Eq. (8).

$$\rho_{fb} = 0.85\beta_1 \frac{f_c'}{f_{fu}} \frac{E_f \varepsilon_{cu}}{E_f \varepsilon_{cu} + f_{fu}} \tag{8}$$

5.2 Analysis result of the reliability-based reinforcement ratio

From the probability distribution analysis, the reliability-based reinforcement ratios of FRP bars were assessed corresponding to the reliability index of 3.5 for the replacement ratios of RCA. The results were introduced in Table 5. Based on the 0% replacement ratio of RCA, the reinforcement ratio increased with the increase of the replacement ratio of RCA. This is mainly caused by the decrease of compressive strength of RCA concrete as the replacement ratio of RCA increases. Fig. 4 shows the % change between the compressive strength of RCA concrete and the reinforcement ratio of FRP bars based on the RCA 0% case.

In the case of RCA 100%, which has the lowest compressive strength and the highest strength variation, the reinforcement ratio showed about 17.3% higher than the RCA 0% case, where the compressive strength decreased up to 27.5%. Thus, the decreased effect of the compressive strength of RCA concrete could be compensated with increase of the reinforcement ratio of FRP bars. The relative error between these two ratios can be a useful information in design methodology for flexural members applying FRP bar and RCA concrete.

6. Conclusions

This study is to investigate the reliability-based reinforcement ratio of the target bridge structure reinforced by FRP bar applying RCA concrete. It can be a good approach for concrete structures made of uncertain materials such as FRP bar or recycled aggregate concrete. Conclusion is as follows.

1. The statistical characteristics of FRP bars and RCA concrete were investigated from the previous literatures and the mean value and standard deviation were summarized. Based on the statistics, a reliability analysis process was proposed.

2. The reliability-based reinforcement ratios of FRP bars were investigated according to the replacement ratios of RCA. These ratios were assessed corresponding to the reliability index of 3.5. It was found that the compressive strength reduction of RCA concrete could be compensated with increase of the reinforcement ratio of FRP bars. It can be a useful information in structural design for FRP bar reinforced concrete structures applying RCA.

3. It can be a good approach for concrete structures made of uncertain materials such as FRP bar or recycled aggregate concrete. The material statistics can be updated by employing more material database. In particular, the strength factors for material property of FRP bars and recycled aggregate concrete can be further updated then it can feedback to the reliability-based reinforcement ratio.

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References

AASHTO LRFD Bridge Design Specifications (2014), *American Association of State Highway and Transportation Officials (AASHTO)*, Washington, D.C., U.S.A.

Abdul-Salam, B., Farghaly A.S. and Benmokrane B. (2016), "Mechanisms of shear resistance of one-way concrete slabs reinforced with FRP bars", *Constr. Build. Mater.*, **127**(30), 959-970.

ACI440 Committee (2015), *Guide for the Design and Construction of Concrete Reinforced with FRP Bars (ACI440.1R-15)*, American Concrete Institute, Farmington Hills, Michigan, U.S.A.

Ahmed, E.A., El-Salakawy, E.F. and Benmokrane, B. (2010), "Performance evaluation of GFRP shear reinforcement for concrete beams", *ACI Struct. J.*, **107**(1), 53-62.

Ajdukiewicz, A. and Kliszczewicz, A. (2002), "Influence of recycled aggregates on mechanical properties of HS/HPC", *Cement Concrete Compos.*, **24**(2), 269-279.

Arioglu, N., Girgin Canan, Z. and Arioglu, E. (2006), "Evaluation of ratio between splitting tensile strength and compressive strength for concretes up to 120 MPa and its application in strength criterion", *ACI Mater. J.*, **103**, 18-24.

Arora, S. and Singh, S.P. (2016), "Analysis of flexural fatigue failure of concrete made with 100% coarse recycled concrete aggregates", *Constr. Build. Mater.*, **102**(15), 782-791.

Bouguerra, K., Ahmed, E.A., El-Gamal, S. and Benmokrane, B. (2011), "Testing of full-scale concrete bridge deck slabs reinforced with fiber-reinforced polymer (FRP) bars", *Constr. Build. Mater.*, **25**(10), 3956-3965.

Choi, H.B., Shin, Y.S., An, S.H., Chung, H.S. and Kang, K.I. (2007), "A properties and durability of recycled aggregate concrete", *J. Architect. Inst. Kor. Struct. Constr.*, **23**(9), 125-132.

Corinaldesi, V. (2010), "Mechanical and elastic behaviour of concretes made of recycled-concrete coarse aggregates", *Constr. Build. Mater.*, **24**(9), 1616-1620.

Deng F., He, Y., Zhou, S., Yu, Y., Cheng, H. and Wu, X. (2018), "Compressive strength prediction of recycled concrete based on deep learning", *Constr. Build. Mater.*, **175**(30), 562-569.

Duan, Z.H. and Poon, C.S. (2014), "Properties of recycled aggregate concrete made with recycled aggregates with different amounts of old adhered mortars", *Mater. Des.*, **58**, 19-29.

El-Nemr, A., Ahmed, E.A., El-Safty, A. and Benmokrane, B. (2018), "Evaluation of the flexural strength and serviceability of concrete beams reinforced with different types of GFRP bars", *Eng. Struct.*, **173**(15), 606-619.

Jeon, E., Yun, H.D., Ji, S.K., Choi, K.S., You, Y.C. and Kim, K.H. (2009), "Mechanical properties of ready-mixed concrete with recycled coarse aggregates", *J. Architect. Inst. Kor. Struct. Constr.*, **25**(8), 103-110.

Ju, M., Oh, H. and Sun, J.W. (2014), "Simplified reliability estimation for optimum strengthening ratio of 30-year-old double T-beam railway bridge by NSM techniques", *Math. Probl. Eng.*, **2014**, 734016.

Ju, M., Park, K. and Park, C. (2018), "Punching shear behavior of two-way concrete slabs reinforced with glass-fiber-reinforced polymer (GFRP) bars", *Polym.*, **10**(8), 893.

Ju, M., Park, Y. and Park, C. (2017), "Cracking control comparison in the specifications of serviceability in cracking for FRP reinforced concrete beams", *Compos. Struct.*, **182**(15), 674-684.

Keum, J.J., Jang, H.S., Hong, S.U., Lee, Y.T. and Cho, Y.S. (2011), "A study on the comparison of compressive strength of concrete with mixed fly ash according to the replacement ratio of recycled coarse aggregate", *Proceeding of the Architectural Institute of Korea*, **31**(2), 289-290.

Korea Construction Specification (KSC 14 20 21:2016) (2016), *Recycled Aggregate Concrete*, Ministry of Land, Infrastructure and Transport of Korea.

Kurda, R., Brito, J. and Silvestre, J.D. (2018), "Indirect evaluation of the compressive strength of recycled aggregate concrete with high fly ash ratios", *Mag. Concrete Res.*, **70**(4), 204-216.

Kwan, W.H., Ramli, M., Kam, K.J. and Sulieman, M.Z. (2012), "Influence of the amount of recycled coarse aggregate in concrete design and durability properties", *Constr. Build. Mater.*, **26**(1), 565-573.

Lee, B.C., Lee, J., Cho, Y.K. and Jung, S.H. (2015), "The strength and length change properties of recycled aggregate concrete (RAC) by compressive strength levels", *J. Kor. Recycled Constr. Res. Inst.*, **3**(4), 307-312.

Li, T., Zhu, H., Wang, Q., Li, J. and Wu, T. (2018), "Experimental study on the enhancement of additional ribs to the bond performance of FRP bars in concrete", *Constr. Build. Mater.*, **185**(10), 545-554.

Malešev, M., Radonjanin, V. and Marinković, S. (2010), "Recycled concrete as aggregate for structural concrete production", *Sustainab.*, **2**(5), 1204-1225.

Maranan, G.B., Manalo, A.C., Benmokrane, B., Karunasena, W. and Mendis, P. (2015), "Evaluation of the flexural strength and serviceability of geopolymer concrete beams reinforced with glass-fibre-reinforced polymer (GFRP) bars", *Eng. Struct.*, **101**(15), 529-541.

Medina, C., Zhu, W., Howind, T., De Rojas, M.I.S. and Frías, M. (2014), "Influence of mixed recycled aggregate on the physical-mechanical properties of recycled concrete", *J. Clean. Prod.*, **68**, 216-225.

Montero, J. and Laserna, S. (2017), "Influence of effective mixing water in recycled concrete", *Constr. Build. Mater.*, **132**, 343-352.

Nanni, A. (2001), "Relevant field applications of FRP composites in concrete structures", *J. Struct. Eng.*, **119**(11), 3344-3359.

Pantelides, C.P., Liu, R. and Reaveley, L.D. (2012), "One-way shear behavior of lightweight concrete panels reinforced with GFRP bars", *J. Compos. Constr.*, **16**(1), 2-9.

Pilakoutas, K., Neocleous, K. and Guadagnini, M. (2002), "Design philosophy issues of fibre reinforced polymer reinforced concrete structures", *J. Compos. Constr.*, **6**(3), 154-61.

Poon, C., Shui, Z., Lam, L., Fok, H. and Kou, S. (2004), "Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete", *Cement Concrete Res.*, **34**(1), 31-36.

Qin, R., Zhou, A. and Lau, D. (2017), "Effect of reinforcement ratio on the flexural performance of hybrid FRP reinforced concrete beams", *Compos. Part B: Eng.*, **108**(1), 200-209.

Rahal, K. (2007), "Mechanical properties of concrete with recycled coarse aggregate", *Build. Environ.*, **42**(1), 407-415.

Rao, M.C., Bhattacharyya, S. and Barai, S. (2011), "Influence of field recycled coarse aggregate on properties of concrete", *Mater. Struct.*, **44**(1), 205-220.

Schubert, S., Hoffmann, Cathleen, Leemann, A., Moser, K. and Motavalli, M. (2012), "Recycled aggregate concrete: Experimental shear resistance of slabs without shear reinforcement", *Eng. Struct.*, **41**, 490-497.

Seara-Paz, S., Gonzalez-Fonteboa, B., Martinez-Abella, F. and Eiras-Lopez, J. (2018), "Flexural performance of reinforced concrete beams made with recycled concrete coarse aggregate", *Eng. Struct.*, **156**(1), 32-45.

Silva, R.V., Brito, J. and Dhir R.K. (2015), "Tensile strength behaviour of recycled aggregate concrete", *Constr. Build. Mater.*, **83**(15), 108-118.

Sim, J. and Park, C. (2011), "Compressive strength and resistance to chloride ion penetration and carbonation of recycled aggregate concrete with varying amount of fly ash and fine recycled aggregate", *Waste Manage.*, **31**(11), 2352-2360.

Tam, V.W.Y., Gao, X.F. and Tam, C.M. (2006), "Comparing performance of modified two-stage mixing approach for producing recycled aggregate concrete", *Mag. Concrete Res.*, **58**(7), 477-484.

Tsoumani, A., Matikas, T. and Barkoula, N. (2014), "Influence of recycled aggregates on compressive strength of concrete", *Proceedings of the 2nd International Conference on Sustainable Solid Waste Management, Athens*.

Wambeke, B. and Shield, C. (2006), "Development length of glass fiber reinforced polymer bars in concrete", *ACI Struct. J.*, **103**(1), 11-17.

World Commission on Environment and Development (1987), *Our Common Future*, United Nations World Commission on Environment and Development (WCED).

Xiao, J., Li, J. and Zhang, C. (2005), "On statistical characteristics of the compressive strength of recycled aggregate concrete", *Struct. Concrete*, **6**(4), 149-153.

Yang, I.H. and Jeong, J.Y. (2016), "Effect of recycled coarse aggregate on compressive strength and mechanical properties of concrete", *J. Kor. Concrete Inst.*, **28**(1), 105-113.

Zain, M.F.M., Mahmud, H.B., Ilham, A. and Faizal, M. (2002), "Prediction of splitting tensile strength of high-performance concrete", *Cement Concrete Res.*, **32**(8), 1251-1258.

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