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Shearing Strength and Reliability of Recycled Concrete Beams

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Abstract: The shearing behaviour of recycled concrete beams is studied here, by putting forward the formula for calculating shearing strength of recycled concrete beams and then assessing their reliability therefore. Based on the comparison between the experimental data by domestic and overseas researchers and the calculated results by formula from the code for design of concrete structures (GB 50010-2010) (CDCS), the applicability of the CDCS for the recycled concrete beams is validated statistically. According to the analysis of factors affecting the shearing strength of beams, the feasibility of the CDCS for the recycled concrete beams bending capacity is examined. The reliability analysis of the recycled concrete beams shearing capacity is carried out by Monte Carlo method. It is shown that the formula from the CDCS is too conservative to calculate the shearing strength of recycled concrete beams as well as that of ordinary concrete beams. When the average compressive strength of the recycled concrete is increased to achieve the same standard compressive strength of recycled concrete as that of ordinary concrete, the reliability of recycled concrete beams is proved to meet the specification requirements.

Key words: Recycled concrete beams, shearing strength, reliability analysis, monte carlo method

INTRODUCTION

The idea of recycling of aggregates has been introduced into practice many years ago and from the beginning it has been considered in two main environmental aspects: solving the growing waste disposal crisis and protection of depleted natural sources of aggregates. In the last decades it has also become an economical problem, as the prices of good natural aggregates were significantly increased in many regions (Xiao *et al*., 2008a).

Up to the present, the results of tests presented in different countries have been mainly concerned with material properties obtained from concrete specimens prepared with various recycled aggregates. A few tests have been done on structural members, particularly made from high-strength concrete. Such tests are necessary because it is difficult to predict the influence of the combination of differences in particular properties on the overall behavior of reinforced concrete members made from recycled aggregate concrete (Xiao *et al*., 2008b).

Shear behaviour of beams using recycled aggregate concrete has been experimentally studied by many researchers in the past (Masaru *et al*., 2004; Xiao and Lan, 2006). Test results showed that cracking patterns and the failure mode of recycled concrete beams are similar to those of ordinary concrete beams, while the shearing strength is little lower than that of ordinary concrete beams because of the lower tensile strength on the condition of same mix proportion.

Due to the different sources of waste concrete, the difference of recycled coarse aggregate performance resulted from a mass of factors, such as mixture ratio, working life, exposure conditions and the degree of damage, magnifies variability of material properties of recycled concrete, such as compressive strength, elastic modulus. This magnified variability of recycled concrete materials performance would increase the variability of shearing strength of recycled concrete beams, eventually leading to reduction of structural security. In this paper, based on a deeply comparative analysis between the relative experimental data by domestic and overseas, calculated method of recycled beams shearing strength is proposed and then reliability analysis of recycled concrete beams shearing strength is carried out. The aim of this paper is to clarify various doubts of designers about the safety of using recycled concrete in structures (Etxeberria *et al*., 2004).

SHEARING STRENGTH OF RECYCLED CONCRETE BEAMS

In order to explore that whether the shearing strength formula from the Code has the same practical significance not only for the ordinary concrete beams but also for the recycled concrete beams, that is to say whether the

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formula of ordinary concrete beams shearing strength can be applied to recycled concrete beams, a comparative analysis between previous experimental data and calculated value of the formula obtained from the Design of Concrete Structures GB50010 (2010) (here in after referred to as the "Code") is performed. Since test methods vary from different countries, such as tests for concrete axially-tensile strength, the necessary conversion for the corresponding data is made.

Factors affecting shearing strength of recycled concrete beams: Taking into account similar elements made from concrete of the same mixture proportions but using different aggregates, it is difficult to predict their failure shape, load-bearing capacity, deflection etc. Such a situation was found with the introduction of recycled aggregates. However, based on previous tests on differences of properties of concrete made from particular recycled aggregates, comparison of observations and results of tests may be concluded as follows: the pattern of cracking and the shape of failure of recycled concrete beams is similar to those of ordinary beams and modified truss is valid in estimating the shearing resisting force of stirrup covering recycled as well as ordinary concrete (Xiao *et al*., 2008a).

There are many factors affecting shearing strength of a beam, such as concrete strength, shear span ratio, stirrup ratio and size of the beam.

Masaru *et al*. (2004), Belen and Martinez (2004), Yagishita *et al*. (1993) and other people made an experimental study on shearing strength of different grade of recycled concrete beams without web reinforcement. The test results showed that there was a linear relationship between shearing strength of recycled concrete beams and grade of recycled concrete, which is the same as ordinary concrete beams. Han *et al*. (2001) studied on the shearing strength of recycled concrete beams without web reinforcement under the different shear span ratio and the test results show that the larger the shear span ratio, the lower the shearing strength of recycled concrete beams without web reinforcement, which is similar to ordinary concrete beams. Belen and Martinez (2004) and Mukai and Kikuchi (1988) studied on influences of different stirrup ratio on the shearing strength of recycled concrete beams and the results showed that there was approximatively linear relationship between the shearing strength of recycled concrete beams with web reinforcement and stirrup ratio.

Based on the existing experimental data from domestic and abroad of recycled concrete beams, a preliminary study on the main factors, that is recycled concrete strength, shear span ratio and stirrup ratio, that impact recycled concrete beams with or without web

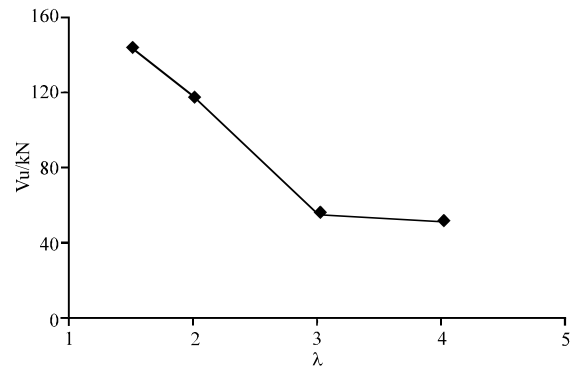

Fig. 1: The comparative result of different shear span ratio

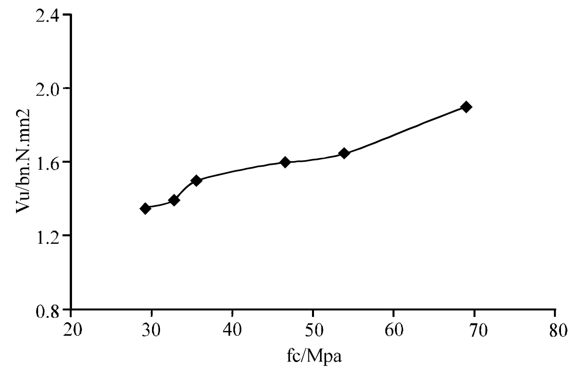

Fig. 2: The comparative result of different grade of recycled concrete

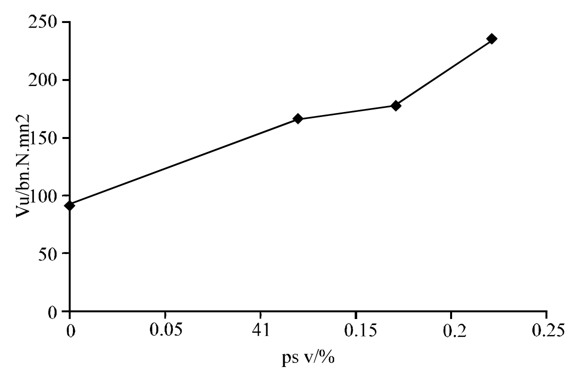

Fig. 3: The comparative result of different stirrup ratio

reinforcement concrete is carried out. According to test results of Masaru *et al*. (2004), Han *et al*. (2001) and Belen and Martinez (2004), relationship between shearing strength of recycled concrete beams and axial compressive strength of recycled concrete, shear span ratio and stirrup ratio are shown in Fig. 1-3. Conclusion can be drawn from this figure that shearing strength of recycled concrete beam increases with the increase of recycled concrete and stirrup ration,

Table 1: The ration of experimental results and calculated results (Xp) of ordinary concrete beams without web reinforcement

Researcher	No.	Exp.V_u/bh_0/ N/mm^2	Cal.V_u/bh_0/ N/mm^2	Exp.V_u/ Cal. V_u
B.C.Han	C2.0-N	2.57	1.24	2.07
Miren	HC-1	1.63	0.94	1.74
Belen	V0CC	1.46	0.90	1.62
	V0CCS	1.65	0.90	1.83
Masaru	VC30	2.3	1.61	1.43
	VC45	1.9	1.14	1.66
	VC60	1.88	0.94	1.99
Mean value				1.76
The coefficient of variation				0.22

Table 2: The ration of experimental results and calculated results (Xp) of recycled concrete beams with web reinforcement

Researcher	No.	Exp.V_u/bh_0 /N/mm^2	Cal.V_u/bh_0 /N/mm^2	Exp.V_u /Cal.V_u
B.C.Han	R2.0-W1	2.26	1.69	1.94
	R2.0-W2	2.24	2.29	1.46
	R2.0-W5	1.94	3.22	1.18
	R2.0-W8	2.24	4.67	0.81
	NR2.0-W2	2.13	2.22	1.39
Miren	HR25-2	2.28	2.11	1.45
	HR25-3	2.28	1.83	1.52
	HR50-2	2.25	2.10	1.73
	HR50-3	2.25	1.82	1.59
	HR100-2	2.20	2.08	1.50
	HR100-3	2.20	1.80	1.49
Belen	V24RC	2.34	1.60	1.66
	V24RCS	2.34	1.60	1.49
	V17RC	2.21	1.81	1.59
	V17RCS	2.21	1.81	1.73
	V13RC	2.29	2.11	1.79
	V13RCS	2.29	2.11	1.55
Lan Yang	BS50	1.77	2.67	1.35
	BS100	1.74	2.65	1.26
Mukai	Arecycled 15	2.09	3.20	1.38
	Arecycled 30	2.05	3.17	1.28
	Brecycled 15	2.09	4.88	1.31
	Brecycled 30	2.05	4.85	1.26
Yagishita	BR1	2.45	3.16	1.47
	BR2	2.65	3.31	1.40
	BR3	3.04	3.62	1.34
Mean value				1.46
The coefficient of variation				0.22

while decreases with increase of shear span ratio, which is similar to ordinary concrete beams.

Statistical analysis of the results for shearing strength: The above discussion seems to imply that the formula from CDCS which is applied to predict shearing strength of ordinary concrete beams may be used to calculate the shearing strength of recycled concrete as well. In order to further prove that, shearing strength test results form 23 recycled concrete beams without web reinforcement in the literature (from Belen and Martinez (2004) to Xiao and Lan (2006), which included 16 recycled concrete beams and 7 ordinary concrete beams and 39 beams with web reinforcement which included 26 recycled concrete beams and 13 ordinary concrete beams are collected. In these tests, the axial compressive strength of recycled concrete and normal concrete ranges from 20 to 60 MPa and yield strength of reinforcement varies from 300~410 MPa. For test methods vary from different country (such as concrete axial compressive strength, etc.), the necessary conversion of corresponding data is made in this study. The ratio of test results and calculated results in accordance with the formula from CDCS is defined as the resistance uncertainty coefficient X_P which is shown in Table 1-4.

Table 3: the ration of experimental results and calculated results (Xp) of recycled concrete beams without web reinforcement

Researcher	No.	Exp.V_u/bh_0 /N/mm^2	Cal.V_u/bh_0 /N/mm^2	Exp.V_u /Cal.V_u
B.C.Han	R1.5-N	3.14	1.54	2.04
	R2.0-N	2.56	1.11	2.30
	R3.0-N	1.2	0.84	1.42
	R4.0-N	1.11	0.68	1.63
	NR2.0-N	2.47	1.15	2.15
Miren	HR25-1	1.68	0.94	1.78
	HR50-1	1.44	0.93	1.55
	HR100-1	1.36	0.91	1.50
Belen	V0RC	1.49	0.90	1.66
	V0RCS	1.38	0.90	1.53
Masaru	CRC30	1.9	1.27	1.50
	CFRC30	1.65	1.11	1.49
	CRC45	1.6	1.02	1.56
	CFRC45	1.5	0.88	1.70
	CRC60	1.4	0.85	1.66
	CFRC60	1.35	0.79	1.70
Mean value				1.79
The coefficient of variation				0.26

From Table 1-4, it is shown that shearing strength of ordinary concrete beams and recycled concrete beams according to the formula from CDCS are larger than the calculated value, that is to say, formula from CDCS is a little conservative for both. At this point, the formula from CDCS can ben applied to predict shearing strength of recycled beams.

ANALYSIS OF SHEARING RELIABILITY OF RECYCLED CONCRETE BEAMS

Example for reliability analysis: In order to analyze the shearing strength of recycled concrete beams, a beam is supposed, whose rectangular section as shown in Fig. 4.

The strength grade of concrete is C30 and the strength grade of steel is HRB335. To ensure it is balanced-reinforcement beam, the range of beam's steel ratio is from 0.3-2.0%.

For any steel ratio of beam, its performance function can be expressed as:

$$Z = V_R(f_c, f_y)-V_S(G, Q) \quad (1)$$

where, V_R is structural resistance of section, V_S is load effect.

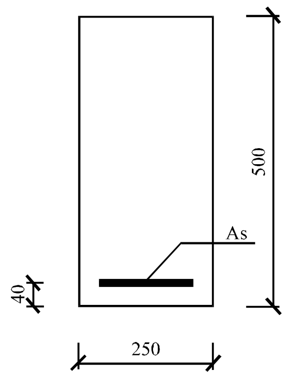

Fig.4: Beam section (mm)

Table4: The ration of experimental results and calculated results (Xp) of ordinary concrete beams with web reinforcement

Researcher	No.	Exp.V_u/bh_0 /N/mm^2	Cal.V_u/bh_0 /N/mm^2	Exp.V_u /Cal.V_u
B.C.Han	C2.0-W2	2.44	3.36	1.38
Miren	HC-2	2.10	2.26	1.08
	HC-3	1.83	2.26	1.24
Belen	V24CC	1.60	2.07	1.30
	V24CCS	1.60	2.43	1.52
	V17CC	1.81	2.44	1.35
	V17CCS	1.81	3.23	1.79
	V13CC	2.11	3.08	1.46
	V13CCS	2.11	3.56	1.69
Lan Yang	BS0	2.58	4.00	1.55
Mukai	A-	3.10	4.70	1.52
	B-	4.77	5.67	1.19
Yagishita	B	3.47	4.80	1.38
Mean value				1.42
The coefficient of variation				0.19

Table 5: Parameter distribution of the beam

Symbol	Mean value	The coefficient of variation
b	250 mm	0.03
h_0	460mm	0.02
f_{yv}	266MPa	0.07
ρ_{sv}	Variable	0.07
f_t	Variable	Variable
λ	Variable	0.03

Table 6: Parameter of the concrete

Parameter	Type I	Type II	Type III
f_{cuk}	30MPa	26.7MPa	30MPa
μ_{fcu}	38.2MPa	38.2MPa	43.2MPa
σ_{fcu}	5MPa	7.5MPa	7.5MPa
δ_{fcu}	0.13	0.18	0.18
μ_{ft}	2.55MPa	2.55MPa	2.92MPa
f_{tk}	2.01MPa	1.79MPa	2.01MPa
f_t	1.43MPa	1.27MPa	1.43MPa

The Matlab program is weaved to calculate bending reliability of beams by Monte Carlo method.

Statistics of resistance V_R: Since collected specimens are all under the concentrated load, so we apply the formula (7.5.4-4) from the CDCS to calculate V_R as following:

$$V_R = \frac{1.75}{\lambda+1} f_t b h_0 + f_{yv} \rho_{sv} b h_0 \quad (2)$$

To study the affect of stirrup ratio, shear span ratio and grade of concrete on shearing reliability of beams, the distribution of the resistance parameters of shearing strength of recycled concrete and ordinary concrete beams are shown in Table 5, which is according to the the Code for design of concrete structure (Xiao *et al*., 2010) and Yang and Zhao(1999). In this paper, the stirrup ratio λ is taken as 0.003-0.02, shear span ratio is taken as 1.5, 2.2, 3 and concrete strength is listed in Table 6.

In Table 6, type I is the statistical parameters of ordinary concrete beams while type and type are statistical parameters of recycled concrete beams. In comparison with type I, Since the standard deviation of compressive strength of recycled concrete is larger than that of ordinary concrete, the standard value of compressive strength of recycled concrete is lower than that of ordinary concrete on the condition of the same mean value of compressive strength, as shown in type. In the same way, compared with type I, the mean value of compressive strength of recycled concrete is larger than that of ordinary concrete on the condition of the same standard value of compressive strength, as shown in type. That is say, in order to reach the same grade of strength, the mean value of recycled concrete should be increased. The tensile strength distribution of recycled concrete used is according to test results of Yuan Biao. And for he type, the distribution of resistance uncertainty coefficient X_P adopted is according to the statistical results in Table 1-4.

Statistics of load effect V_S: Only permanent load G and office persistent of life load on floor Q are considered. According to the literature, the former whose coefficient of variation is taken as 0.07 follows a normal distribution; and the latter whose coefficient of variation is taken as 0.292 follows the type I of extreme value distribution (Architectural reliability design unified standard. The mean value of permanent load G can be carried out by its standard value multiplied by 1.06. While the mean value of office persistent of life load on floor Q can be carried out by its standard value multiplied by 0.406.

Based on the ultimate state of design, distribution of load effect $V_{s,d}$ depends on the load type and bearing capacity of cross-section.

$$V_{S,d} = \frac{1.75}{\lambda+1} f_t b h_0 + f_{yv} \rho_{sv} b h_0 \quad (3)$$

$$f_{yv} = \frac{f_{yvk}}{\gamma_s} = 210\text{MPa},\ f_t = 1.43\text{MPa} \quad (4)$$

Considering three types of load, when the first type is 100% permanent load, the distribution of the load effects $V_{S,G}$ can be expressed as:

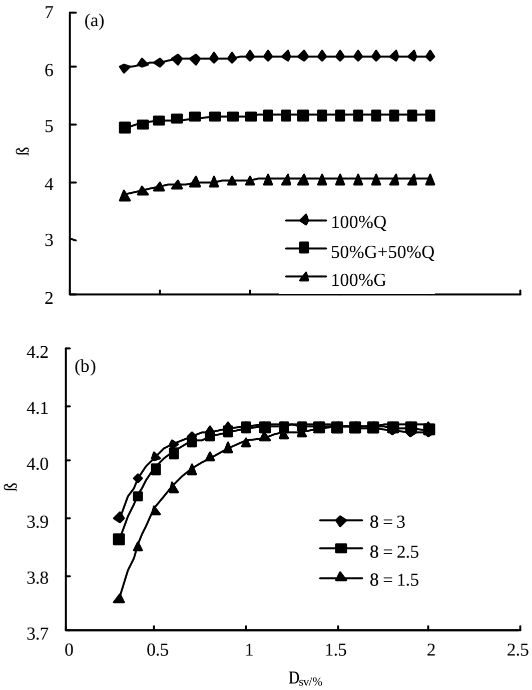

Fig.5(a-b): (a) The effect of load type and shear span ratio on the reliability index of ordinary concrete beams and (b) The effect of load type The effect of shear span ratio

$$V_{S,G} \sim N(\frac{V_{S,d}}{\gamma_G} \times 1.06, \delta_G = 0.07) \quad (5)$$

where, $\gamma_G = 1.35$.

The second type of load is the100% persistence life load on floor, distribution of load effect $M_{S,Q}$ can be expressed as:

$$V_{S,Q} \sim N(\frac{V_{S,d}}{\gamma_Q} \times 0.406, \delta_Q = 0.292) \quad (6)$$

where, $\gamma_Q = 1.40$.

The third type of load is that the ratio of the permanent load and persistence life load on floor is 1:1, the distribution of the load effects can be expressed as:

$$V_{S,G+Q} \sim N(\frac{V_{S,d}}{(\gamma_G + \gamma_Q)} \times 1.06, \delta_G = 0.07) + N(\frac{V_{S,d}}{(\gamma_G + \gamma_Q)} \times 0.406, \delta_Q = 0.292) \quad (7)$$

where, $\gamma_G = 1.2$, $\gamma_Q = 1.40$.

Analysis of reliability: The reliability index of ordinary concrete beams under different load types of load along with different steel ratio is shown in Fig. 5a.

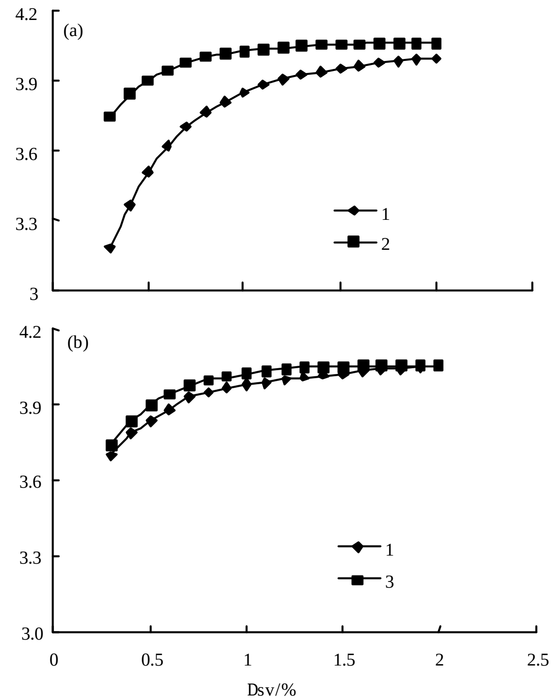

Fig. 6(a-b): The shearing reliability of beams, (a) The comparison between recycle concrete and ordinary concrete and (b) The effect of distribution of compressive strength of concrete

Under three types types of load, the reliability index of the beam meet the code requirements, and that is$\beta \geq 3.7$. While we could also draw a point that among three types of load, the reliability index of the beam under the 100% permanent loads are minimum. Therefore, only on the condition of 100% permanent load are analyzed in the following calculations of shearing reliability of beams to ensure the safety of structures.

On condition that 100% permanent load is carried, the reliability index of beams with different shear span ratios is shown in Fig. 5b. As it shows, reliability index of beams with three types of shear span ratio could meet the specification. With the increase of shear span ratio, beams shearing reliability index increases and with the increase of the stirrup ratio ρ_{sv}, the shearing reliability of beams with different shear span ratio gets more and more consistent gradually. Whereas, we took λ = 1.5 for calculations below because of the minimum reliability index.

Three types of beams are considered in this study, as shown in Table 3 and the shearing reliability of these beams are shown in Fig. 6a-b. From these figures, It concludes that reliability index of beams increases with the increase of the stirrup ratio. In Fig. 6a, for the Type I and II, whose average compressive strength of concrete are equal, it shows that because the standard deviation of compressive strength of recycle concrete is larger than that of ordinary concrete, shearing reliability index of recycled concrete beams are less than ordinary concrete beams and are much closer followed by the increase of stirrup ratio. It follows that as the stirrup rate increases, the shearing reliability of recycled concrete beams reduces the sensitivity to the standard deviation of compressive strength of recycled concrete. In Fig. 7b, for the type I and II, whose standard value of compressive strength of concrete is the same while mean value of recycled concrete is larger than that of ordinary concrete because of the higher standard deviation of compressive strength of recycled concrete, in the whole range of stirrup ratio the shearing reliability of recycled concrete beams is slightly larger than that of ordinary concrete beams, which can meet the requirements of the specification.

CONCLUSION

The following conclusions can be made on the basis of current analysis:

- The pattern of cracking and the shape of failure of recycled concrete beams is similar to those of ordinary beams and modified truss is valid in estimating the shearing resisting force of stirrup covering recycled as well as ordinary concrete
- The trend that Shear span ratio, concrete strength and stirrup ratio impact recycled concrete beams is similar to ordinary concrete beams
- Formula from the CDCS is conservative to calculate shearing strength of recycled concrete beams as well as ordinary concrete beams
- Increasing the average compressive strength of the recycled concrete to achieve the same standard compressive strength of recycled concrete as that of ordinary concrete, for standard deviations of compressive strength of recycled concrete is larger than that of ordinary concrete, the reliability of recycled concrete beams is slightly larger than ordinary concrete beams and can meet the specification requirements

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