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Average Crack Spacing of Overlay-strengthened RC Beams

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Abstract: The research is focused on evaluating the average crack spacing of overlay-strengthened reinforced concrete (RC) beams. The current equations in different structural codes for predicting the average crack spacing of RC beam with multilayered-reinforcing bars is proved to be inapplicable for overlay-strengthened RC beam, although these two kinds of beams are both with reinforcement in multi-layers. Therefore, a simple, practical and new analytical model that is capable of predicting the average crack spacing of overlay-strengthened beams is developed. An overlay-strengthened beam element is analyzed based on equilibrium and compatibility equations to formulate the average stresses of concrete, overlay and tension reinforcement. A series of verification comparisons with the experimental investigations, which involved various types of beam elements, are performed to verify the validity and reliability of the model. The proposed model performs satisfactorily with respect to measured response from the experimental database.

Keyword: crack spacing; overlay; strengthening; interface; bond; multilayered-reinforcement

1. Background

Overlaying is considered as a major retrofitting method for flexural and fatigue strengthening or retrofitting of concrete flexural members. As illustrated in Fig. 1, in this method, the tension reinforcements such as steel bars or Fibre-Reinforced Plastic (FRP) grid are arranged underneath the lower surface of the concrete members and the Polymer Cement Mortar (PCM) or High Performance Fiber Reinforced Cementitious Composites (HPFRCC) is sprayed onto them. In light of the weak bond strength of overlaying with normal cement based materials, the PCM or HPFRCC offers a good compromise of bond strength and durability. Comparing with steel bars as overlay reinforcement, the FRP grid is of low weight and high corrosion resistance and gaining more and more interests recently.

Cracks in overlay-strengthened RC structures may be expected because of the relatively low tensile strength of concrete and overlay materials and the use of high strength reinforcement in substrate and overlay. Cracking in overlay-strengthened RC structures has a major influence on structural performance, including tensile, bending and shear stiffness, energy absorption capacity, ductility and corrosion resistance of reinforcement. Moreover, the average crack spacing of overlay-strengthened beams plays an important role in transferred shear stress along overlay-substrate interface and normal stress generated in the substrate concrete in case when the premature debonding failure is investigated (Zhang et al. 2010; Wang and Ling 1998; Raoof and Hassanen 2000). It is, therefore, necessary to predict the cracking behavior of overlay-strengthened RC beam.

Despite the fact that many design models have been provided by different structural codes or individual researchers with respect to average crack spacing of RC members with single or multilayered-reinforcement (JSCE 2007; EC2 2004; CSA 2004; NS 1992; CEB-FIP 1990; Broms 1965; Albandar and Mills 1974; Břazant and Oh 1983; Rizk and Marzouk 2010; Dawood and Marzouk 2010; Marzouk et al. 2010; Rizkalla et al. 1983; Rizkalla and Hwang 1984), which are similar to overlay-strengthened RC member with reinforcement layers in the substrate and overlay, their applicability for overlay-strengthened beams has not yet been investigated.

The main objective of this study is to develop a rational methodology for predicting the average crack spacing of overlay-strengthened RC beam. Firstly, the predicted average crack spacing based on existing models from several design specifications is compared with that from experimental database. Then a model which is capable of evaluating crack behaviors of both overlay-strengthened beam and conventional RC beam was developed. The analytical approach is based on equilibrium and compatibility equations to formulate the average stresses of concrete, overlay and reinforcement of an overlay-strengthened beam element.

2. Crack spacing approach in the different structural codes

Tensile cracking in reinforced or prestressed concrete members is affected by various factors, such as the types of reinforcement, concrete cover, effective cross sectional area of concrete, diameter of reinforcement, ratio of reinforcement, number of layers of reinforcement, surface geometry of

reinforcement, quality of concrete, magnitude of prestress, etc. Generally, all or some of these parameters are induced in different structural codes.

2.1 JSCE 2007

The value of crack spacing in *JSCE* (2007) is stated by the following equations:

$$S_{cr} = 1.1k_1k_2k_3\{4C + 0.7(c_s - \phi)\} \quad (1)$$

where C denotes concrete cover in mm, c_s and ϕ denote center-to-center distance and diameter of outer-layer tensile reinforcement in mm. k_1 is coefficient that characterizes the effect of surface geometry of reinforcement ($=1.0$ for deformed bars, and $=1.3$ for plain bars and prestressing steel), k_2 is a constant to take into account the effect of concrete quality, which may be calculated as

$$k_2 = \frac{15}{f'_c + 20} + 0.7 \quad (1.1)$$

where f'_c is compressive strength of concrete in MPa. k_3 is a constant to take into account the effect of multiple layers of tensile reinforcement and may be calculated as

$$k_3 = \frac{5(n+2)}{7n+8} \quad (1.2)$$

where n is number of the layers of tensile reinforcement.

2.2 Eurocode EC2 provisions

In the Eurocode *EC2* (2004), the average crack spacing is evaluated from the following expression:

$$S_{cr} = 2C + k_1 k_2 \frac{\phi A_{ct}}{A_{st}} \quad (2)$$

where C denotes concrete cover in mm; ϕ is diameter of outer-layer tensile reinforcement in mm; A_{st}/A_{ct} denotes effective reinforcement ratio with A_{st} =the area of tensile reinforcement and A_{ct} =the effective concrete area (see Fig. 2.a). $k_1=0.8$ for deformed bars and 1.6 for plain bars, and $k_2=0.5$ for bending and =1.0 for pure tension. In this approach, the EC2 code takes only the effect of the concrete cover and ignores the influence of the bar spacing of the outer-layer tension reinforcement.

2.3 CSA S474 2004

According to Canadian offshore code CSA-S474 (2004), the average crack spacing of cracks normal to the reinforcement may be calculated using the following equation:

$$S_{cr} = 2.0(C + 0.1S) + k_1 k_2 \phi / \rho_{tNs} \quad (3)$$

where C denotes concrete cover thickness in mm (not greater than 55 mm); S denotes bar spacing of the outer-layer tension reinforcement in mm; k_1 is coefficient that characterizes bond properties of bars (=0.4 for deformed bars, and =0.8 for plain bars); k_2 is coefficient to account for strain gradient = $0.25 (\varepsilon_1 + \varepsilon_2)/2\varepsilon_1$, ε_1 and ε_2 are the largest; and smallest tensile strains in the effective embedment zone; ϕ is bar diameter of the outer-layer tension reinforcement in mm. ρ_{tNs} is the effective reinforcement ratio, which may be calculated by

$$\rho_{tNs} = A_{st} / h_{eff} b \quad (3.1)$$

where h_{eff} is effective embedment thickness in mm, taken as the greater of $(a_1+7.5\phi')$,and $(a_2+7.5\phi)$, but not greater than the height of tension zone (see Fig. 2.b); b is width of the section in mm; A_{st} is area of reinforcement within the effective embedment thickness in mm^2 .

2.4 NS 3473 E 1992

The Norwegian code *NS-S474E* (1992) provides the similar approach for the calculation of the average crack spacing as that of *CSA-S474* (2004), with only a small difference in the calculation of k_2 and effective reinforcement ratio ρ_{tNS} , as shown in Fig. 2.c.

2.5 CEB-FIP 1990 provisions

The value of the crack spacing in *CEB-FIP* (1990) code is stated by a different expression from previous codes (JSCE 2007; EC2 2004; CSA 2004; NS 1992) as:

$$S_{\max} = \frac{2}{3} l_{s,\max} \quad (4)$$

$$l_{s,\max} = \frac{\phi_s}{3.6\rho_{s,ef}} \quad (4.1)$$

where $l_{s\max}$ is the length over which slip occurs between the steel reinforcement and concrete, ϕ_s denotes the diameter of the outer-layer tension reinforcement in mm, $\rho_{s,ef}$ is the effective reinforcement ratio, which can be calculated as

$$\rho_{s,ef} = \frac{A_s}{A_{c,ef}} \quad (4.2)$$

where A_s denotes the area of steel bars and $A_{c,ef}$ is the effective area of concrete in tension as indicated in Fig. 2.a.

3. Applicability of current models

3.1 Comparison between calculation and experimental results

In order to exam the applicability of the models in different structural codes, the calculated crack spacing with different codes equations should compare with the experimental crack spacing of overlay-strengthened RC beams. For this purpose, published or reported experimental results of overlay-strengthened beams with sufficient dimension and material parameters as well as average crack spacing are analyzed (Furuuchi et al. 2000; Furuuchi et al. 2002; Matsumoto 2000; Satoh and Kodama 2005; Zhang 2009; Zhang et al 2009; Yamamoto 2010; Yamamoto et al. 2010). In total, 36 samples with different material properties and dimensions are collected, in which 26 samples are PCM overlay with steel bars, 8 samples are HPFRCC overlay with FRP grid and 2 samples are PCM overlay with FRP grid. All the test data included in this data base were obtained for simply supported rectangular RC beams subjected to four-point bending load and the average crack spacing is taken as the average spacing of flexure cracks between two upper loading points (constant moment zone). The geometrical and material properties of the collected samples are summarized in Appendix A. The average crack spacing measured at each sample in which the steel bars are used as reinforcement in overlay is presented in Table 1 and Fig. 3 along with numerical estimations based on current models from different codes. The mean value and standard deviation of S_{cal}/S_{exp} are shown in Table 1 as well.

The *JSCE* code equation overestimates the value of average crack spacing with mean value of S_{cal}/S_{exp} equaling to 1.14 and the other four code equations underestimate the value of average crack

spacing with mean value of S_{cal}/S_{exp} ranging from 0.66 to 0.76. Moreover, big scatters can be observed for all the code equations with standard deviation ranging from 0.19 to 0.30. Generally speaking, none of the code equations can give reasonable agreement to measured average crack spacing of overlay-strengthened RC beam. Therefore, the current models in different codes for estimating average crack spacing of RC beam with multilayered-reinforcement can not be applied directly for overlay-strengthened RC beams, although these two kinds of beams are both with reinforcement in multi-layers.

3.2 Explanations on the mismatch

The equations in different design codes for multilayer-reinforced beam should have been verified to be applicable before they are induced as a design approach. The reason why they are incapable of predicting the average crack spacing overlay-strengthened beams needs to be clarified.

Fig. 4 shows the strain distributions across the depth of the cross section of overlay strengthened beam. By assuming that the overlay and the substrate behave monolithically, the moment at the initiation of tensile crack in substrate (M_{cc}) and overlay (M_{co}) can be calculated respectively as:

$$M_{cc} = \frac{I_c}{h_c - x_g} f_{tc} \quad (\text{substrate}) \quad (5)$$

$$M_{co} = \frac{E_c}{E_o} \left(\frac{I_c}{h_o - x_g} \right) f_{to} \quad (\text{overlay}) \quad (6)$$

where f_{tc} and f_{to} denote the tensile strength of concrete and overlay material, E_c and E_o denote the Young's modulus of concrete and overlay material, x_g denotes the neutral axis depth of uncracked

section of overlay strengthened beam and I_c denotes the second moment of transformed area of the uncracked cross section in terms of concrete. The ratio between M_{cc} and M_{co} is then expressed as:

$$R_c = \frac{M_{cc}}{M_{co}} = \frac{E_o (h_o - x_g) f_{tc}}{E_c (h_c - x_g) f_{to}} \quad (7)$$

For conventional beam with multilayered-reinforcement ($E_c=E_o$, $f_{tc}=f_{to}$), the value of R_c is always greater than 1, which means the tensile crack always initiates near to the outer-layer reinforcement.

While in case of the overlay strengthened beam samples as shown in appendix A ($E_c>E_o$, $f_{tc}<f_{to}$), the maximum value of R_c is 0.52 with a mean value of 0.45, which means the tensile crack always initiates from the substrate concrete . This agrees with the experimental observations as well.

Most of the present research work and existing analytical models for predicting cracking behavior of beams with multilayered-reinforcement consider only the effects of the diameter and spacing of outer-layer reinforcement, which is nearest to the initiation location of tensile crack. However in case of overlay-strengthened beam, the cracks tend to initiate from the substrate concrete and propagate towards the overlay, as a result of relative high tensile strength and low Young's modulus of overlay materials. Therefore, it is reasonable that the properties of reinforcement in the substrate instead of overlay should be used in the equations of different codes. Table 2 and Fig. 5 show the calculated average crack spacing by using the diameter and spacing of tension reinforcement in the substrate, comparing with experimental results. Much better agreements can be achieved with modified models from CSA (2004), NS (1992) , EC2 (2004) and CEB-FIP (1990), but there is no apparent improvement with modified models from JSCE (2007), since both the diameter and the

spacing of reinforcement are dominant in *CSA* (2004), *NS* (1992) , *EC2* (2004) and *CEB-FIP* (1990), but not in *JSCE* (2007). However it is not confident enough to apply this substitution simply for the valid prediction of average crack spacing of overlay strengthened beam because all the equations in different codes are only empirical models and the cracking mechanism in the overlay-strengthened beam is not clear yet. Moreover, all the existing equations are meant for members with steel reinforcing bars. None of them may be applicable to the overlay strengthened beam with FRP grid as reinforcement in overlay, since steel bar diameters are needed for calculation. An analytical approach considering the stresses of concrete, overlay and reinforcement of overlay strengthened beam element based on equilibrium and compatibility equations is then developed for a better understanding of cracking behavior of overlay strengthened beam with either steel bars or FRP grid as tension reinforcement.

4. Analytical model

When a segment of overlay strengthened beam is subjected to uniaxial tension loading which is greater than the cracking load of both substrate concrete and overlay, the idealized cracked beam section is assumed to consist of the effective tensile area of concrete and overlay, and reinforcement in the concrete and overlay as illustrated in Fig. 6.a. For a section between two adjacent cracks, the bond between the concrete or overlay and the reinforcement restrains the elongation of reinforcement, and part of the tensile stress in the reinforcement is transmitted to the concrete or overlay consequently (Sato and Kodama 2005).

Fig. 6.a shows a longitudinal segment of overlay strengthened beam between two adjacent cracks subjected to uniaxial tensile force. The length of this segment S represents the crack spacing. The free body diagram of the substrate and overlay elements with length of dx is shown in Fig. 6.b. The equilibrium of forces acting on the concrete and overlay segment can be written as follows:

$$\begin{cases} F = F + dF + \sum O_r \tau_{bc}(x) dx + \sum O_s \tau_{bo}(x) dx \\ \frac{dF}{dx} = -(\sum O_r \tau_{bc}(x) + \sum O_s \tau_{bo}(x)) \\ \frac{d\sigma_c(x)}{dx} A_{ct} + \frac{d\sigma_o(x)}{dx} A_{ot} = -(\sum O_r \tau_{bc}(x) + \sum O_s \tau_{bo}(x)) \end{cases} \quad (8)$$

where $\tau_{bc(x)}$ and $\tau_{bo(x)}$ denote the bond stress at the reinforcement-concrete interface and the reinforcement-overlay interface at the stabilized crack stage, which is assumed to follow a parabolic variation as shown in Fig. 6.c. The peak bond stress τ_{bcm} or τ_{bom} occurs at the midsection between the two zero points. This bond stress distribution closely agrees with the experimental observations according to Jiang et al. (1984) and Kankam (1997). O_r and O_s denote the perimeter of reinforcement in concrete and overlay respectively, A_{ct} and A_{ot} denote the effective tension area of concrete and overlay. For a certain steel bar or FRP grid, the maximum area of the reinforced concrete (A_{cmax}) or overlay (A_{omax}) zone within which stable crack can develop is,

$$A_{c(o)max} = \frac{A_{s(F)} \cdot f_{y(Fy)}}{f_{c(o)t}} \quad (9)$$

where $A_{s(F)}$ and $f_{y(Fy)}$ denote the area, the yielding strength of steel bar (FRP Grid) respectively, $f_{c(o)t}$ is the tensile strength of concrete (overlay). In a two-dimensional consideration, the maximum size of square bond effective zone for steel bar (h_{cmax}) or FRP Grid (h_{omax}) can then be calculated as,

$$h_{c(o)max} = \sqrt{A_{c(o)max}} \quad (10)$$

In case of bending, the maximum height of effective zone should not be higher than the tension area (area which is below the neutral axis) as shown in Fig. 2.d. Moreover, the reduction of concrete tension area due to existence of transverse reinforcements or stirrups is considerably small and ignored in this analysis.

For a given element between two adjacent cracks, the expected location for the maximum concrete or overlay tensile stress is at the midway (zero-slip point). At the stabilized crack stage, the tensile stress of concrete or overlay at the zero-slip point cannot be greater than the tensile strength f_{ct} or f_{ot} respectively, regardless of load increase. This condition corresponds to the stabilized crack spacing S_{cs} , for the case in which the concrete tensile stress $\sigma_c = f_{ct}$ or S_{os} , for the case in which the overlay tensile stress $\sigma_o = f_{ot}$.

Since tensile strains in the substrate concrete and overlay are released after cracking and both concrete and overlay can behave monolithically, we can assume that the concrete and overlay have the same strain ε_o at zero-slip point at the primary crack formation stage under uniaxial tension load, which means

$$\varepsilon_o = \frac{\sigma_{cs}}{E_c} = \frac{\sigma_{os}}{E_o} \quad (11)$$

where σ_{cmax} and σ_{omax} denote the maximum tensile stress in concrete and overlay at the zero-slip point. Since the substrate and overlay.

Based on Eq.8 and Eq.11, the following equations can be derived:

$$\begin{aligned} \sigma_{cs}A_{ct} + \sigma_{os}A_{ot} &= \int_{S/2}^0 - \left(\sum O_r \tau_{bc}(x) + \sum O_s \tau_{bo}(x) \right) dx \\ &= \frac{-S \left(\sum O_r \tau_{bcm} + \sum O_s \tau_{bom} \right)}{3} \\ \sigma_{cs} &= \frac{S \left(\sum O_r \tau_{bcm} + \sum O_s \tau_{bom} \right)}{3 \left(A_{ct} + A_{ot} \frac{E_o}{E_c} \right)} \leq f_{ct} \\ \sigma_{os} &= \frac{S \left(\sum O_r \tau_{bcm} + \sum O_s \tau_{bom} \right)}{3 \left(A_{ct} \frac{E_c}{E_o} + A_{ot} \right)} \leq f_{ot} \end{aligned} \quad (12)$$

Stablized crack spacing of substrate concrete layer is then expressed as:

$$S_{cs} = \frac{3f_{ct} \left(A_{ct} + A_{ot} \frac{E_o}{E_c} \right)}{\left(\sum O_r \tau_{bcm} + \sum O_s \tau_{bom} \right)} \quad (13)$$

Stabilized crack spacing of overlay layer is expressed as:

$$S_{os} = \frac{3f_{ot} \left(A_{ct} \frac{E_c}{E_o} + A_{ot} \right)}{\left(\sum O_r \tau_{bcm} + \sum O_s \tau_{bom} \right)} \quad (14)$$

The bond stress between reinforcement and concrete or overlay depends primarily on the compressive strength, the cover thickness of concrete or overlay, and on the surface condition of reinforcement. Due to the existence of cross ribs in the surface of FRP grid, which has similar function of ribs in the surface of steel bar, the bond properties of overlay-FRP grid interface can be assumed to be similar as that of steel bar-concrete interface. The peak bond stress τ_{bcm} or τ_{bom} as shown in Fig. 6.b is then calculated using the fib Model Code equation (2010) as follows:

$$\text{in case of splitting failure } \tau_{bc(o)m} = 5.5 \cdot \left(\frac{f'_{c(o)}}{20} \right)^{0.25} \quad \text{with transverse reinforcement} \quad (15)$$

$$\tau_{bc(o)m} = 5.0 \cdot \left(\frac{f'_{c(o)}}{20} \right)^{0.25} \quad \text{without transverse reinforcement} \quad (16)$$

$$\text{in case of pull - out failure } \tau_{bc(o)m} = 1.25 \sqrt{f'_{c(o)}} \quad (17)$$

where $f'_{c(o)}$ denotes the cylinder compressive strength of concrete(overlay).

In beam with small concrete cover and clear spacing between the reinforcement, transverse reinforcement provides the most relevant confining effect, especially in zones far from direct supports where external pressure is not present (Untrauer and Henry, 1965; Gambarova and Rosati, 1997). It is assumed that the confining effect of transverse steel bar or FRP grid in the overlay is similar as that of stirrup in the substrate concrete.

Once the crack initiates in either layer of concrete or overlay, it will propagate to another layer due to the reduction of stiffness of cracked section, therefore the stabilized crack spacing of overlay strengthened composite S_s depends on the lesser of S_{cs} and S_{os} , which means

$$S_s = \min(S_{cs}, S_{os}) \quad (18)$$

Considering the effect of strain gradient, the average crack spacing of overlay strengthened beam under flexure load can be predicted as follows:

$$S_{sf} = k_1 \min(S_{cs}, S_{os}) \quad (19)$$

where k_1 is the coefficient to account for strain gradient $= (\varepsilon_1 + \varepsilon_2)/2\varepsilon_1$ according to CSA S474 (2004), ε_1 and ε_2 are the largest; and smallest tensile strains in the effective embedment zone as illustrated in Fig. 2.d, k_1 has the maximum value of 1 in case of uniaxial load and minimum value of 0.5.

The maximum and minimum crack spacing at the stabilized cracking stage can then be determined by assuming the maximum crack spacing (S_{maxsf}) is twice of the minimum crack spacing (S_{minsf}) as

$$S_{\max sf} = \frac{4}{3} S_{sf} \quad (20)$$

$$S_{\min sf} = \frac{2}{3} S_{sf}$$

It should be noted that the proposed model assumes the monolithic responding of overlay and substrate concrete, therefore it is not applicable for the case when debonding between substrate and overlay occurs.

Eqs.13-19 can also be used for conventional RC beam with single or multilayered-reinforcement ($E_c=E_o, f_{tc}=f_{to}$), both Eq.13 and Eq.14 has same result of average crack spacing as:

$$S_s = \frac{3k_1 f_{ct} (A_{ct} + A_{ot})}{\tau_{bcm} (\sum O_r + \sum O_s)} = \frac{3k_1 f_{ct} A_t}{\tau_{bcm} \sum O_{rs}} \quad (21)$$

where $\sum O_{rs}$ denotes the total perimeter of tension reinforcement, and A_t denotes the entire efficient tension area.

5. Verification

The same database is used for verifying the applicability of proposed analytical model for overlay with steel bars as tension reinforcement. Beside, 10 additional samples with FRP grid as reinforcement in overlay are calculated to verify the applicability of proposed analytical models for overlay with FRP grid as tension reinforcement. Moreover, 8 conventional RC beam samples with single or double layer steel reinforcement and with various dimension and reinforcement ratio as shown in Appendix B are collected in order to verify the applicability of proposed model to the conventional RC beam with single or multilayered-reinforcement. Due to the existence of transverse reinforcement in the overlay of all specimens, Eq.15 is used for calculation of maximum

bond shear stress of both substrate concrete layer and overlay layer. The calculation results of overlay strengthened beams are shown in Table 2 and Fig. 7.a. The S_{cs} is always smaller than S_{os} for all the samples because of relative high tensile strength and low Young's modulus of overlay materials, which means the crack of substrate concrete dominates the average crack spacing of overlay strengthened beam. This explains the reason why the developed model can predict the average crack spacing of overlay strengthened beams more precisely than the current structural codes, in which the out-layer (overlay) reinforcements always control. The mean value of S_{cal}/S_{exp} is 1.01 with standard deviation of 0.11. The comparison between calculation and experiment results of conventional beams with single or multilayered-reinforcement based on existing structural codes or proposed model is shown in Table 3 and Fig. 7.b. The *JSCE* code (2007) gives the most conservative prediction. The mean value of S_{cal}/S_{exp} is 1.05 with standard deviation of 0.08 by using the proposed model. For either overlay strengthened or conventional RC beam with single or multilayered-reinforcement, the analytical values have a satisfactorily agreement with the experimental values, which verifies the accuracy of the proposed model, indicating that the proposed prediction method is applicable and reliable.

6. Conclusions

This paper shows that the current models in different structural codes for estimating average crack spacing of beams with multilayered-reinforcement are inaccurate for overlay-strengthened RC beams with reinforcement layers in both the substrate concrete and overlay, although these two kinds of beams are similar to each other in a sense that the reinforcement is arranged in multilayers.

The different initiation location of tensile cracks between the substrate concrete and overlay is considered to be one of main explanations on this mismatch. However it is not convincing enough to apply the substitution in the current structural codes simply for the valid prediction of average crack spacing since the cracking mechanism is not clear. Moreover, the existing empirical equations can not be applied for overlay strengthened beam with FRP grid as reinforcement in overlay.

A crack spacing model is then developed by considering the equilibrium and compatibility equations of overlay strengthened beam element. The new model can account for the influence of major parameters, such as the quantities and total perimeters of reinforcement across the crack, the tensile strength of substrate concrete and overlay materials, the characteristics of the bond between the concrete and reinforcement in the substrate and the bond between the overlay materials and reinforcement in the overlay.

To validate the proposed model, the predicted values of the average crack spacing based on the proposed model are compared with series of experimental investigations, which involved various types of beam elements. The proposed model performs satisfactorily with respect to measured response from the experimental work for both steel bars or FRP grid reinforced overlay and conventional RC beam with single or multilayered-reinforcement. Therefore, this model can be applied as a practical way for predicting the accurate average stabilized crack spacing in designing overlay strengthened or conventional RC beams.

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References

- Albandar, F. A-A., and Mills, G. M.(1974). “The prediction of crack width in reinforced concrete beams”, *Magazine of Concrete Research*, V. 26, No. 88, 153-160.
- Bázant, Z. P., and Oh, b. H. (1983). “Crack spacing in reinforced concrete: approximate solution”, *Journal of Structural Engineering, ASCE*, V. 109, No. 1, 93-108.
- Broms, B. B. (1965). “Crack width and crack spacing in reinforced concrete members”, *Journal of American Concrete Institute, Proceedings*, V. 62, No. 10, 1237-1265.
- Canadian Standard Associations (2004). S474 concrete structures. Mississauga (Ontario, Canada): Canadian Standard Associations.
- Comite Euro-International Du Beton. CEB-FIP model code (1990). Lausanne Switzerland): Comité Euro-Internationale du Beton et Federation Internationale e la Procontrainte.
- Dawood, N., Marzouk, H. (2010). “An analytical approach for crack spacing of thick reinforced concrete plates”, *Engineering Structures* 32, 472-482.
- EC2, Eurocode 2 (2004). Design of concrete structures_Part I: General rules and rules or buildings. Paris: European Committee for Standardization.
- Fib model code (2010), first complete draft, bulletin 55/1, International Federation for Structural Concrete.
- Furuuchi, H., Kakuta, Y., Nishimuta, K., Shimizu, M. and Tokunaga, T., (2002). “Load carrying capacity of RC beam strengthened with sprayed overlay”, *proceedings of 57th annual conference of JSCE*, v, 619-620 (in Japanese).
- Furuuchi, H., Tsuneoka, S., Kakuta, Y. and Yoshizumi, A. (2000). “Research on RC members strengthened with sprayed overlay”, *Proceedings of JCI*, June, Vol.22, No.1, 523-528 (in Japanese).
- Gambarova, P.G., and Rosati, G.P. (1997). “Bond and Splitting in bar Pull-out: Behavioral Laws and Concrete Cover Role”. *Magazine of Concrete Research*, 49(179):99-110.
- Jiang, D., Shah, S. P, and Andonian, A. (1984). “Study of the Transfer of Tensile Forces by Bond, *ACI Structural Journal*, V. 81, No. 3, May-June, 251-259.
- JSCE. Standard specification for concrete structures (2007): Design. Japan Society of Civil Engineerings.
- Kankam, C., (1997), “Relationship of Bond Stress, Steel Stress, and Slip in Reinforced Concrete,” *Journal of Structural Engineering, ASCE*, V. 123, No. 1, 79-85.
- Marzouk, H., Hossin, M.,Hussein, A. (2010), “Crack width estimation for concrete plates”, *ACI Structural Journal*,V. 107, No. 3, 282-290.

- Matsumoto, Y. (2000). "Static and fatigue properties of overlay strengthened beams", *Bachelor graduation thesis*, Hokkaido University (in Japanese).
- Norwegian Council for Building Standardization (1992). NS34773E Concrete structures design rules. Norway: Norwegian Council for Building Standardization.
- Raof, M., Hassanen, MAH. (2000). "Peeling failure of reinforced concrete beams with fibre-reinforced plastic or steel plates glued to their soffits". *Proceedings of the Institution of Civil Engineers, Structures and Buildings*, 140(August), 291–305.
- Rizk, E. and Marzouk, H. (2010). "A new formula to calculate crack spacing for concrete plates", *ACI Structural Journal*, V. 107, No. 1, 43-52.
- Rizkalla, S.H., Hwang, L.S., El-Shahawi, M. (1983). "Transverse reinforcement effect on cracking behavior of R.C. members", *Canad Journal of Civil Engineering*, 10(4), 556-81.
- Rizkalla, S.H., Hwang, L.S. (1984). "Crack prediction for members in uniaxial tension", *ACI Structural Journal*, 81(4), 572-9.
- Satoh, K. and Kodama, K. (2005). "Central Peeling Failure Behavior of Polymer Cement Mortar Retrofitting of Reinforced Concrete Beams", *Journal of Materials in Civil Engineering*, ASCE/ March/April, 126-136.
- Untrauer, R.E. and Henry, R.L. (1965). "Influence of Normal Pressure on Bond Strength", *ACI Journal*, Proceedings, 62(5): 577-586.
- Wang, C.Y., Ling, F.S. (1998). "Prediction model for the debonding failure of cracked RC beams with externally bonded FRP sheets". *Proceedings of the Second International Conference of Composites in Infrastructure (ICCI)*, Arizona, USA, 548–562.
- Yamamoto, T. (2010a). "Capacities and failure mode of beam strengthened with HPFRCC and FRP grid under static and fatigue load", *Bachelor graduation thesis*, Hokkaido University (in Japanese).
- Yamamoto, T., Kikuchi, Y., Zhang, D.W., Furuuchi, H., Ueda, T., Tamura, T., Morii, N., Saitoh, T. (2010b). "Static Load and Failure Mode of Beam strengthened with HPFRCC and FRP Grid overlay", *Proc. of Hokkaido Chapter of the JSCE*, E-19, February (in Japanese).
- Zhang, D.W., Ueda, T., and Furuuchi, H. (2010). "IC debonding of polymer cement mortar (PCM) overlay strengthened RC beam", *Journal of Materials in Civil Engineering*, ASCE (posted ahead of print).
- Zhang, D.W. (2009). "Interface and beam behaviour of PCM-strengthened concrete", *PhD graduation thesis*, Hokkaido University.
- Zhang, D.W., Furuuchi H., Hori A. and Ueda T. (2009). "Fatigue Degradation Properties of PCM-concrete Interface", *Journal of Advanced Concrete Technology*, JCI, Vol. 7, No. 3, 425-438.
- Zhao, W.J., Maruyama, K. (1994). "Experimental study on flexural cracking of RC beams with multi-layers of longitudinal bars", *Journal of Materials, Concrete Structures and Pavement*, JSCE, No. 490, V-23, 137-145.

Figure Caption List

Fig. 1 Typical view of overlay strengthening

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Fig. 3 Comparison with original current equations

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Fig. 7 Comparison with new proposed model

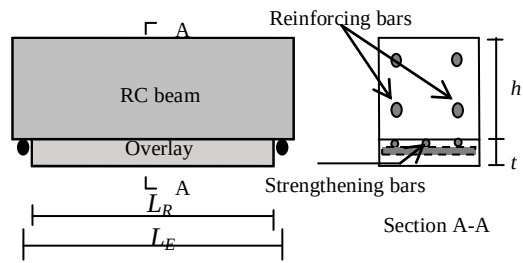


Fig.1 Typical view of overlay strengthening

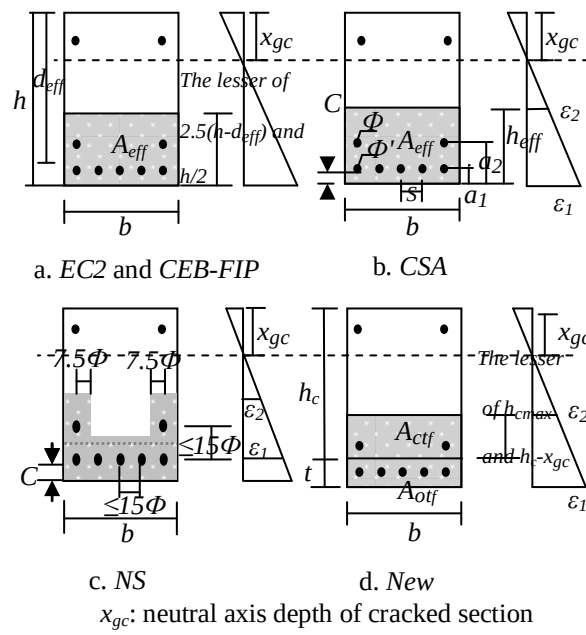


Fig.2 Effective embedded area

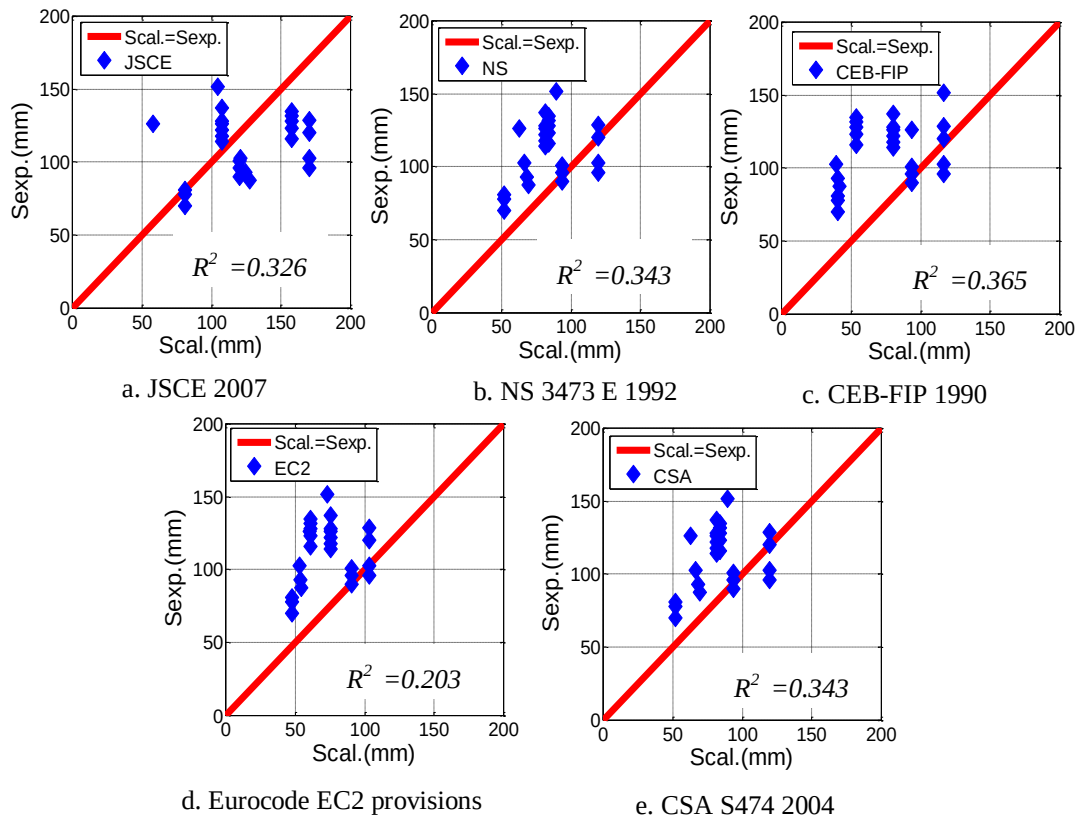


Fig. 3 Comparison with original current equations

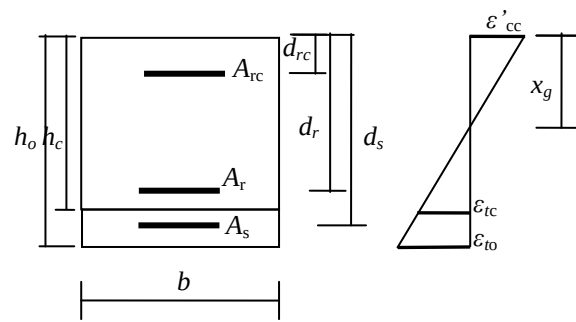


Fig. 4 Sectional analysis of overlay strengthened beam

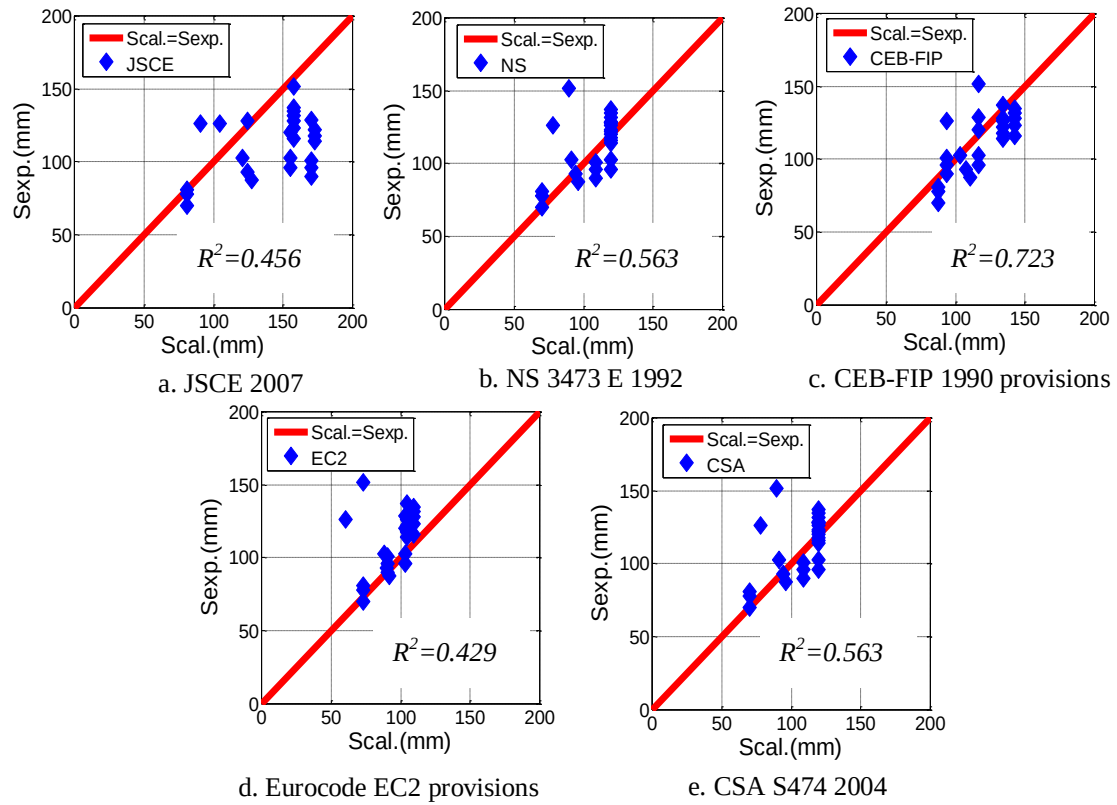


Fig. 5 Comparison with modified current equations

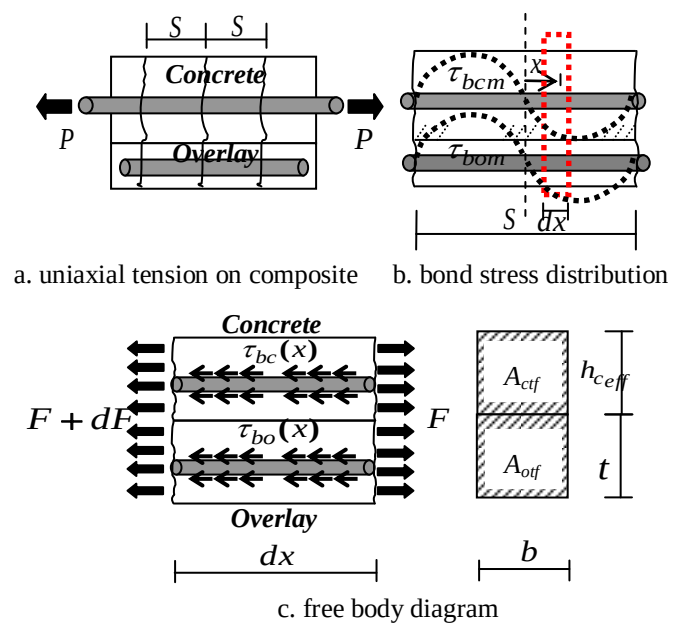
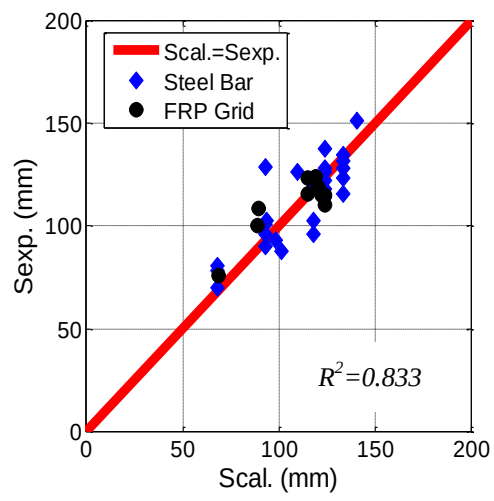
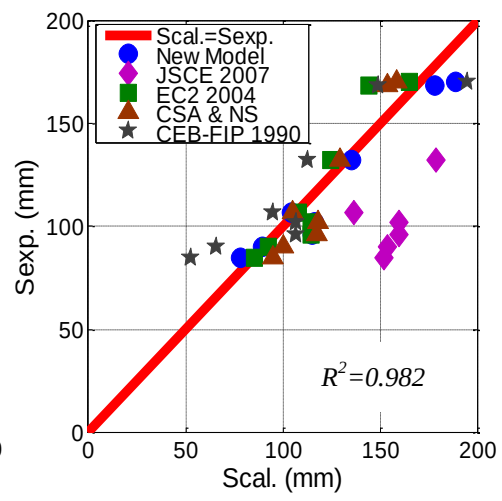


Fig.6 Element analysis of composite



a. Overlay strengthened RC beam



b. Conventional RC beam

Fig.7 Comparison with new proposed model

Table 1 Calculation with original equations from different codes¹⁾

<i>Spe. number</i>	Calculated average crack spacing (mm)					Experimental results (mm)
	<i>JSCE</i>	<i>EC2</i>	<i>CSA</i>	<i>NS</i>	<i>CEB-FIP</i>	
<i>PS1</i>	157.91	60.92	83.64	83.64	53.56	128.00
<i>PS2</i>	157.91	60.92	83.64	83.64	53.56	135.00
<i>PS3</i>	157.91	60.92	83.64	83.64	53.56	132.00
<i>PS4</i>	157.91	60.92	83.64	83.64	53.56	123.33
<i>PS5</i>	157.91	60.92	83.64	83.64	53.56	116.00
<i>PS6</i>	80.96	47.78	51.55	51.55	40.34	70.00
<i>PS7</i>	80.96	47.78	51.55	51.55	40.34	78.00
<i>PS8</i>	80.96	47.78	51.55	51.55	40.34	80.63
<i>PS9</i>	124.7	53.84	67.98	67.98	40.44	92.86
<i>PS10</i>	120.68	52.97	66.07	66.07	38.83	102.50
<i>PS11</i>	127.37	54.41	69.26	69.26	41.51	87.50
<i>PS12</i>	107.65	75.42	81.73	81.73	80.41	128.41
<i>PS13</i>	107.65	75.42	81.73	81.73	80.41	126.36
<i>PS14</i>	107.65	75.42	81.73	81.73	80.41	137.50
<i>PS15</i>	170.63	103.09	119.64	119.64	116.83	128.91
<i>PS16</i>	107.65	75.42	81.73	81.73	80.41	117.86
<i>PS17</i>	170.63	103.09	119.64	119.64	116.83	120.31
<i>PS18</i>	120.31	90.47	93.52	93.52	93.46	100.78
<i>PS19</i>	107.65	75.42	81.73	81.73	80.41	122.19
<i>PS20</i>	170.63	103.09	119.64	119.64	116.83	102.50
<i>PS21</i>	120.31	90.47	93.52	93.52	93.46	96.25
<i>PS22</i>	107.65	75.42	81.73	81.73	80.41	114.00
<i>PS23</i>	170.63	103.09	119.64	119.64	116.83	96.00
<i>PS24</i>	120.31	90.47	93.52	93.52	93.46	90.00
<i>PS25</i>	104.73	73.09	89.17	89.17	116.83	151.60
<i>PS26</i>	58.13	60.47	63.03	63.03	93.46	126.60
Mean of <i>Scal/Sexp</i>	1.14	0.66	0.76	0.76	0.68	—
Standard deviation of <i>Scal/Sexp</i>	0.30	0.19	0.19	0.19	0.25	—

Table 2 Calculation with modified equations from different codes and proposed model

Spe. number	Calculated average crack spacing (mm)							Experimental results (mm)
	JSCE	EC2	CSA	NS	CEB-FIP	Proposed model		
						Sc	So	
PS1	157.91	109.13	119.71	119.71	142.83	133.71	510.18	128.00
PS2	157.91	109.13	119.71	119.71	142.83	133.71	510.18	135.00
PS3	157.91	109.13	119.71	119.71	142.83	133.71	510.18	132.00
PS4	157.91	109.13	119.71	119.71	142.83	133.71	510.18	123.33
PS5	157.91	109.13	119.71	119.71	142.83	133.71	510.18	116.00
PS6	80.96	73.20	69.70	69.70	87.41	68.3	183.42	70.00
PS7	80.96	73.20	69.70	69.70	87.41	68.3	183.42	78.00
PS8	80.96	73.20	69.70	69.70	87.41	68.3	183.42	80.63
PS9	124.7	90.23	94.29	94.29	107.83	98.78	270.48	92.86
PS10	120.68	87.92	91.20	91.20	103.55	93.68	281.58	102.50
PS11	127.37	91.77	96.35	96.35	110.69	101.62	268.09	87.50
PS12	124.43	104.37	119.89	119.89	134.02	124.11	401.41	128.41
PS13	90.88	104.37	119.89	119.89	134.02	124.11	401.41	126.36
PS14	157.98	104.37	119.89	119.89	134.02	124.11	401.41	137.50
PS15	170.63	103.09	119.64	119.64	116.83	93.42	378.82	128.91
PS16	173.32	104.37	119.89	119.89	134.02	124.11	401.41	117.86
PS17	155.30	103.09	119.64	119.64	116.83	118.38	378.82	120.31
PS18	170.63	90.47	108.52	108.52	93.46	93.42	294.85	100.78
PS19	173.32	104.37	119.89	119.89	134.02	124.11	401.41	122.19
PS20	155.30	103.09	119.64	119.64	116.83	118.38	378.82	102.50
PS21	170.63	90.47	108.52	108.52	93.46	93.42	294.85	96.25
PS22	173.32	104.37	119.89	119.89	134.02	124.11	401.41	114.00
PS23	155.30	103.09	119.64	119.64	116.83	118.38	378.82	96.00
PS24	170.63	90.47	108.52	108.52	93.46	93.42	294.85	90.00
PS25	157.98	73.09	89.17	89.17	116.83	140.53	239.75	151.60
PS26	104.73	60.47	78.03	78.03	93.46	110.01	185.21	126.60
HF1	—	—	—	—	—	89.71	165.23	108.80
HF2	—	—	—	—	—	119.53	546.66	124.30
HF3	—	—	—	—	—	68.78	309.47	75.60
HF4	—	—	—	—	—	89.08	405.63	100.30
HF5	—	—	—	—	—	120.4	540.07	119.38
HF6	—	—	—	—	—	122.38	548.93	115.00
HF7	—	—	—	—	—	124.35	557.79	110.40
HF8	—	—	—	—	—	124.35	557.79	115.00
PF1	—	—	—	—	—	115.34	441.73	123.33
PF2	—	—	—	—	—	115.34	441.73	115.90
Mean of Sc/Sc _{exp}	1.29	0.87	0.97	0.97	1.07	1.01		
Standard deviation	0.28	0.14	0.15	0.15	0.13	0.11		

Table 3 Conventional RC beams with single or double layer tension reinforcement

Num. of layer	Spe. number	Calculated average crack spacing (mm)						Experimental results (mm)
		JSCE	EC2	CSA	NS	CEB-FIP	New Model	
Two layers¹⁾	C5	159.87	114.72	118.07	118.07	106.88	115.29	102.00
	C6	159.87	114.72	117.55	117.55	106.88	109.97	96.00
	C7	154.00	92.39	100.06	100.06	65.55	89.35	90.00
	C8	152.11	85.46	94.84	94.84	52.71	78.57	85.00
One layer²⁾	C1	212.52	144.56	153.73	153.73	149.19	178.35	168.50
	C2	136.79	108.30	105.04	105.04	95.00	104.67	107.00
	C3	179.16	124.83	129.30	129.30	112.64	135.53	132.50
	C4	208.98	165.15	158.90	158.90	194.71	188.93	170.45
Mean of Scal/Sexp		1.48	1.02	1.05	1.05	0.91	1.05	
Standard deviation of Scal/Sexp		0.23	0.10	0.12	0.12	0.18	0.08	

1) without stirrup

2) with stirrup

Appendix A. Details of overlay strengthened beam samples

a. Substrate beam								
<i>Spe. serial</i>	<i>Spe. Number*</i>	Efficient length	Width	Height	Shear Span	Concrete		
		L_{eff} (mm)	b (mm)	h_c (mm)	a (mm)	f'_c (MPa)	f_{ct} (MPa)	E_c (MPa)
(Furuuchi et al. 2002)	PS1¹⁾	2200	200	200	800	38.1	2.60	3.04E+04
	PS2	2200	200	200	800	38.1	2.60	3.04E+04
	PS3	2200	200	200	800	38.1	2.60	3.04E+04
	PS4	2200	200	200	800	38.1	2.60	3.04E+04
	PS5	2200	200	200	800	38.1	2.60	3.04E+04
(Furuuchi et al. 2000)	PS6	1300	150	200	450	34.0	2.41	2.92E+04
	PS7	1600	150	200	600	34.0	2.41	2.92E+04
	PS8	2000	150	200	800	34.0	2.41	2.92E+04
(Matsumoto 2010)	PS9	2270	151	200	785	38.7	2.63	3.06E+04
	PS10	2270	145	200	785	38.7	2.63	3.06E+04
	PS11	2270	155	200	785	38.7	2.63	3.06E+04
	PS12	1380	200	150	460	38.0	2.70	3.37E+04
	PS13	1380	200	150	460	38.0	2.70	3.37E+04
	PS14	2070	200	150	690	38.0	2.70	3.37E+04
	PS15	2070	200	150	690	38.0	2.70	3.37E+04
	PS16	2070	200	150	690	38.0	2.70	3.37E+04
(Sato and Kodama 2005)	PS17	2070	200	150	690	38.0	2.70	3.37E+04
	PS18	2070	200	150	690	38.0	2.70	3.37E+04
	PS19	2760	200	150	920	38.0	2.70	3.37E+04
	PS20	2760	200	150	920	38.0	2.70	3.37E+04
	PS21	2760	200	150	920	38.0	2.70	3.37E+04
	PS22	2760	200	150	920	38.0	2.70	3.37E+04
	PS23	2760	200	150	920	38.0	2.70	3.37E+04
	PS24	2760	200	150	920	38.0	2.70	3.37E+04
(Zhang 2009)	PS25	1380	200	150	460	60.0	3.53	3.40E+04
	PS26	1380	200	150	460	60.0	3.53	3.40E+04
(Yamamoto 2010)	HF1²⁾	1380	200	150	460	43.2	2.83	3.16E+04
	HF2	1380	200	150	460	43.2	2.83	3.16E+04
	HF3	1380	200	150	460	43.2	2.83	3.16E+04
	HF4	1380	200	150	460	43.2	2.83	3.16E+04
	HF5	1380	200	150	460	41.6	2.76	3.13E+04
(Yamamoto et al. 2010)	HF6	1380	200	150	460	41.6	2.76	3.13E+04
	HF7	1380	200	150	460	41.6	2.76	3.13E+04
	HF8	1380	200	150	460	41.6	2.76	3.13E+04
(Furuuchi et al. 2002)	PF1³⁾	2200	200	200	800	38.1	2.60	3.04E+04
	PF2	2200	200	200	800	38.1	2.60	3.04E+04

1) **PS**: PCM with steel bar overlay

2) **HF**: HPFRCC with FRP grid overlay

3) **PF**: PCM with FRP grid overlay

b. Reinforcement in substrate beam							
<i>Spe. serial</i>	<i>Spe. number</i>	Compression reinforcement			Tension reinforcement		
		<i>Num.</i>	$\phi_{rc}(mm)$	$d_{rc}(mm)$	<i>Num.</i>	$\phi_r(mm)$	$d_r(mm)$
(Furuuchi et al. 2002)	PS1	1	16	40	2	16	160
	PS2	1	16	40	2	16	160
	PS3	1	16	40	2	16	160
	PS4	1	16	40	2	16	160
	PS5	1	16	40	2	16	160
(Furuuchi et al. 2000)	PS6	2	10	35	3	13	165
	PS7	2	10	35	3	13	165
	PS8	2	10	35	3	13	165
(Matsumoto 2010)	PS9	1	16	40	2	16	160
	PS10	1	16	40	2	16	160
	PS11	1	16	40	2	16	160
	PS12	2	10	30	2	10	115
	PS13	2	10	30	2	10	115
	PS14	2	10	30	2	10	115
	PS15	2	10	30	2	10	115
	PS16	2	10	30	2	10	115
(Sato and Kodama 2005)	PS17	2	10	30	2	10	115
	PS18	2	10	30	2	10	115
	PS19	2	10	30	2	10	115
	PS20	2	10	30	2	10	115
	PS21	2	10	30	2	10	115
	PS22	2	10	30	2	10	115
	PS23	2	10	30	2	10	115
	PS24	2	10	30	2	10	115
(Zhang 2009)	PS25	2	10	31	2	10	116
	PS26	2	10	31	2	10	116
(Yamamoto 2010)	HF1	2	13	30	3	13	120
	HF2	2	13	30	2	13	120
	HF3	2	13	30	3	13	120
	HF4	2	13	30	2	13	120
	HF5	2	13	30	2	13	120
(Yamamoto et al. 2010)	HF6	2	13	30	2	13	120
	HF7	2	13	30	2	13	120
	HF8	2	13	30	2	13	120
(Furuuchi et al. 2002)	PF1	1	16	40	2	16	160
	PF2	1	16	40	2	16	160

c. Overlay properties									
Spe. serial	Spe. number	Overlay material				Tension reinforcement			
		t (mm)	f'_o (MPa)	f_{ot} (MPa)	E_o (MPa)	Num.	ϕ_s (mm)	d_s (mm)	L_o (mm)
(Furuuchi et al. 2002)	PS1	22	24.0	3.20	1.00E+04	2	6	203	2000
	PS2	22	24.0	3.20	1.00E+04	2	6	203	2000
	PS3	22	24.0	3.20	1.00E+04	2	6	203	2000
	PS4	22	24.0	3.20	1.00E+04	2	6	203	2000
	PS5	22	24.0	3.20	1.00E+04	2	6	203	2000
(Furuuchi et al. 2000)	PS6	30	33.1	3.18	1.49E+04	3	6	214	1200
	PS7	30	33.1	3.18	1.49E+04	3	6	214	1500
	PS8	30	33.1	3.18	1.49E+04	3	6	214	1900
(Matsumoto 2010)	PS9	22	30.0	3.35	1.45E+04	2	6	203	2020
	PS10	22	30.5	3.35	1.32E+04	2	6	203	2022
	PS11	22	29.8	3.18	1.43E+04	2	6	203	2006
	PS12	22	27.6	2.89	1.21E+04	3	6	153	1280
	PS13	22	27.6	2.89	1.21E+04	3	6	153	1280
	PS14	22	27.6	2.89	1.21E+04	3	6	153	1970
	PS15	30	27.6	2.89	1.21E+04	2	10	155	1970
	PS16	22	27.6	2.89	1.21E+04	3	6	153	1970
(Sato and Kodama 2005)	PS17	30	27.6	2.89	1.21E+04	2	10	155	1970
	PS18	30	27.6	2.89	1.21E+04	3	10	155	1970
	PS19	22	27.6	2.89	1.21E+04	3	6	153	2660
	PS20	30	27.6	2.89	1.21E+04	2	10	155	2660
	PS21	30	27.6	2.89	1.21E+04	3	10	155	2660
	PS22	22	27.6	2.89	1.21E+04	3	6	153	2660
	PS23	30	27.6	2.89	1.21E+04	2	10	155	2660
	PS24	30	27.6	2.89	1.21E+04	3	10	155	2660
(Zhang 2009)	PS25	30	57.4	3.80	2.34E+04	2	10	170	1280
	PS26	30	57.4	3.80	2.34E+04	3	10	170	1280
(Yamamoto 2010)	HF1	15	57.4	3.80	2.34E+04	2	4x6*	154	1280
	HF2	15	42.5	4.50	1.14E+04	2	4x6*	154	1280
	HF3	15	42.5	4.50	1.14E+04	4	4x6*	154	1280
	HF4	15	42.5	4.50	1.14E+04	4	4x6*	154	1280
	HF5	10	23.9	4.50	1.14E+04	2	4x4.5*	152	1280
(Yamamoto et al. 2010)	HF6	15	23.9	4.50	1.14E+04	2	4x4.5*	157	1280
	HF7	20	23.9	4.50	1.14E+04	2	4x4.5*	162	1280
	HF8	20	23.9	4.50	1.14E+04	2	4x4.5*	157	1280
(Furuuchi et al. 2002)	PF1	22	24.0	3.20	1.00E+04	3	4x5*	203	2100
	PF2	22	24.0	3.20	1.00E+04	3	4x5*	203	2100

* Width x Height of FRP grid longitudinal cross section

Appendix B. Details of beam samples with single or multilayered-reinforcement

a. Concrete and compression reinforcement

Spe. serial	Spe. number	Width	Height	Concrete			Compression reinforcement		
		B (mm)	H (mm)	f'_c (MPa)	f'_t (MPa)	E_c (MPa)	Num.	ϕ_{rc} (mm)	d_{rc} (mm)
(Furuuchi et al. 2002)	C1¹⁾	200	200	38.1	2.60	3.04E+04	1	16	40
(Furuuchi et al. 2000)	C2	150	200	34.0	2.41	2.92E+04	2	10	35
(Matsumoto 2010)	C3	151	200	38.7	2.63	3.06E+04	1	16	40
(Sato and Kodama 2005)	C4	200	150	38.0	2.70	3.37E+04	2	10	30
(Zhao and Maruyama 1994)	C5	150	300	29.1	2.17	2.77E+04	—	—	—
	C6	150	300	29.1	2.17	2.77E+04	—	—	—
	C7	150	300	31.3	2.28	2.84E+04	—	—	—
	C8	150	300	31.3	2.28	2.84E+04	—	—	—

1) C: Conventional RC beams

b. Tension reinforcement

Spe. serial	Spe. number	1st tension reinforcement			2st tension reinforcement		
		Num.	ϕ_{r1} (mm)	d_{r1} (mm)	Num.	ϕ_{r2} (mm)	d_{r2} (mm)
(Furuuchi et al. 2002)	C1	1	16	40	—	—	—
(Furuuchi et al. 2000)	C2	2	10	35	—	—	—
(Matsumoto 2010)	C3	1	16	40	—	—	—
(Sato and Kodama 2005)	C4	2	10	30	—	—	—
(Zhao and Maruyama 1994)	C5	2	13	215	2	13	265
	C6	2	13	240	2	13	265
	C7	2	19	240	2	13	265
	C8	2	22	248	2	13	265