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DAMAGE EVALUATION OF RC BEAMS WITH HIGH STRENGTH TRANSVERSE STEEL REINFORCEMENT

A. Benyoucef[(1)], R. Rinaldi[(2)], T. Obara[(3)], S. Kono[(4)], D. Mukai[(5)]

[(1)] *Graduate Student, Tokyo Institute of Technology, benyoucef.a.aa@m.titech.ac.jp*
[(2)] *Graduate Student, Tokyo Institute of Technology, rickyrinaldi04@gmail.co*
[(3)] *Assist. Prof., Tokyo Institute of Technology, obara.t.ac@m.titech.ac.jp*
[(4)] *Prof., Tokyo Institute of Technology, kono.s.ae@m.titech.ac.jp*
[(5)] *Assoc. Prof., University of Wyoming, (Visiting Assoc. Prof., Tokyo Institute of Technology), dmukai@uwyo.edu*

Abstract

Severe damages on buildings and high economic loss due to past earthquakes have shown us the importance of carefully determining damage of structural systems. Cracking is one of the key indicators of the level of damage of reinforced concrete structures. This study presents the crack performance of six reinforced concrete beams with high strength transverse steel reinforcement. The correlation between total shear crack width and the shear component of drift was analyzed according to a model proposed by Architectural Institute of Japan (AIJ) Guidelines 2004. It was confirmed that the shear component of residual drift had good agreement with the summation of the horizontal component of residual shear crack widths. The result of this study can be utilized for the development of assessment procedures of crack widths.

Following recent large earthquakes, many RC buildings in urban areas, which had been designed not to collapses, lost serviceability and were later demolished. Modern seismic design considers quick recovery as one of the most desirable aspects of resilience. Hence, it is important to propose a design procedure that addresses serviceability and recovery in addition to safety. To this end, in addition to the safety limit state, current seismic performance based design procedures include intermediate states. The ASCE 41-17 standard and the 2004 AIJ guidelines can be used as damage evaluation tools to determine the damage level of RC members. However, to implement these guidelines new data on damage due to shear failure is needed to clarify the seismic behavior of RC members. Currently, the criteria in the 2004 AIJ Guidelines, which takes into account the level of residual crack width and strain of concrete and reinforcement, can be applied only to evaluate the damage of reinforced concrete flexural members. To extend this to shear damage, this paper verifies its application to RC beams which failed in shear.

This study uses test results of six RC beams with high strength transverse steel reinforcement to check the correlation between crack width and the shear component of drift. The main parameters included shear reinforcement ratio (0.2%, 0.6% and 1.2%), specified yield strength of longitudinal reinforcement shear reinforcement (685 MPa), and nominal compressive strength of concrete (24 MPa and 42MPa). The relation between crack width and shear component of drift was analyzed according to a model proposed in the 2004 AIJ Guidelines. It was found that the shear component of drift had good agreement with the summation of horizontal components of residual shear crack widths. The findings from this study will be utilized in cost evaluation of reinforced concrete members to achieve more economical and resilient structural system.

Keywords: reinforced concrete; residual crack; limit state; high strength reinforcement.

1. Introduction

After the Tohoku 2011 earthquake, many reinforced concrete (RC) buildings suffered from extensive damage such as cracks and spalling. In some cases, the building were demolished because it was no longer functional. To avoid excessive economic loss due to earthquake, it is important to develop resilient systems that can minimize seismic damage and quickly recover building functionality. The use of high strength materials contributes to reducing reinforcement congestion, reduction of reinforcement ratio, less cost for reinforcement installation, and successful concrete casting. These advantages are especially beneficial during the construction of important buildings such as nuclear power plants and tall buildings. Recently, many researchers investigated the better use of high strength materials to reduce the amount of materials for the construction of tall RC buildings. High strength reinforcement was used to reduce the amount of reinforcement and spacing, as this can improve workability [1]. Munukrishma studied the behavior of concrete beams reinforced with high strength shear reinforcement. Their test results showed that crack width at the serviceability loading stage was within acceptable limits [2, 3]. Lee [4] tested RC beams with high strength shear reinforcement having a shear failure mode. They concluded that the diagonal crack width under the service load level is affected by the yield strength and spacing of stirrups.

Residual crack width is one of the major factors to consider in developing earthquake resilient structural systems for RC structures. Flexural and shear crack behavior has been investigated by many researchers on RC beams [6, 7, 8, 9, 10, 11]. A simple model was proposed in the AIJ Guidelines 2004 [12] to determine crack width from member shear drift component by assuming uncracked concrete as a rigid body. Kono et al [13] evaluated the model by comparing the summation of horizontal component of shear cracks with shear drift component at cycle's peak loads, but the residual shear crack widths haven't been observed. This study presents a shear crack performance of six reinforced concrete beams using high strength steel (SD685) transverse reinforcement. This paper is based on the work of Rinaldi [14, 15, 16]. The AIJ model used in Rinald's work helps for post-earthquake assessment of damage in RC structures. There are two possible applications for this work. First, this study can be used for newly designed buildings. The residual shear drift can be obtained from frame analysis (from either push over or time history analyses). Using this study, the calculated shear drift could be correlated to the expected cracking damage level of the new building after the earthquake used in the analysis. The second application of this work is for existing buildings after an earthquake motion. The cracks of damaged building could be measured at the site and to back-calculate peak shear drift. This residual drift graded by 2004 AIJ Guidelines to determine the damage level of RC beams with high strength reinforcement. Thus, this damage evaluation method helps to estimate the limit states of new and existing buildings. The result of this study can be utilized to determine the damage of earthquake resistant RC structures.

2. Experimental outline

Six RC beams were designed to fail in different modes of failure and these modes of failure were controlled by variables such as transverse reinforcement ratio, concrete compressive strength, shear span ratio and cross section geometry. Table 1 lists the details of the six specimens tested by Rinaldi. From these six specimens, displacement and crack width data were taken to analyze the crack performance.

Crack patterns and the measuring setup (biaxial crack gauge) for the crack width and slip are illustrated in Fig.1. The blue and red lines represent cracks path which developed from loading in positive and negative directions respectively. Crack width (W_{xi}) and slip (W_{yi}) on the positive cracks were digitally measured using the biaxial crack gauges in Fig. 1. The number of crack increased as the load increased. The crack gauges were attached perpendicular to the cracks on the center line as shown on Fig. 1 and Fig. 3. In specimen #5 an additional crack gauge was applied off the centerline.

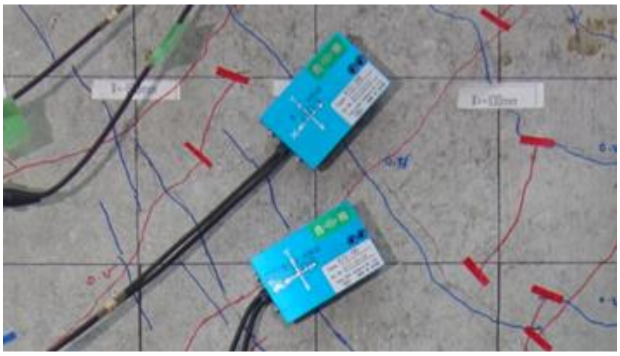


Fig. 1 – Biaxial crack gauges

Table 1 – Beam specimens specifications

No.		#1	#2	#3	#4	#5	#6
Specimen name		B24-02-SS	B24-06-SS	B24-12-SS	B24-02-SL	B60-02-SS	B24-02-XS
f'c (MPa)		23.0	22.7	23.6	24.6	47.2	24.1
B x D (mm)		340 X 450					420 X 560
Clear Span L (mm)		1350			2250	1350	1680
L/2D		1.50			2.50	1.50	
Longitudinal Reinforcement	Configuration	3+3-D25 SD590	3+3-D25 SD590	3+3-D25 SD590	3+3-D25 SD590	3+3-D25 SD590	5+3-D25 SD590
Transverse Reinforcement	Configuration	4D10@210	4D10@70	3D10@52.5	4D10@210	4D10@210	4D10@170
	Yield strength (MPa)	788					
	ρw (%)	0.200	0.600	1.20	0.200		
Role		Shear Standard	Higher ρw	Highest ρw	Larger L/2D	Higher f'c	Larger Section
Expected Failure mode		Shear	Shear	Shear	Shear	Shear	Shear

f'c : compressive strength of cylinders, L: clear span length (mm), D: overall depth (mm)
ρw: shear reinforcement ratio

Shear component of drift (δ_s) was measured using four sets of diagonal displacement gauges as shown in Fig. 2. The total residual shear drift can be obtained by the summation of residual shear drift at each zone. The transverse residual crack width can be obtained from coordinate transformation of the crack gauge measurements. The total transverse residual crack width measured at each residual drift. The top and bottom diagonal gauges were connected to the stub blocks.

3. Deformation calculation

Lateral deformation of the beam was assumed to consist of flexural and shear deformation. Shear deformation (δ_i) for one set of diagonal displacement gauges was calculated by using Eq. (1), where (δ_a) and (δ_b) are the elongation of the diagonal gauges, (H) is the vertical height and (L) is the horizontal length of the gauge set as shown in Fig. 4. Shear deformation calculated from all four sets of diagonal gauges were summed to obtain the specimen's shear component of drift (δ_s). Shear deformation of the beam was computed by Eq. 2.

$$\gamma_i = \frac{\sqrt{H^2 + L^2}}{H.L} . \frac{(\delta_3 - \delta_4)}{2} \; ; \; \delta_{si} = \gamma_i .H \quad (1)$$

$$\delta_s = \sum_{i=1}^{4} \delta_{si} - \delta_{slip} \quad (2)$$

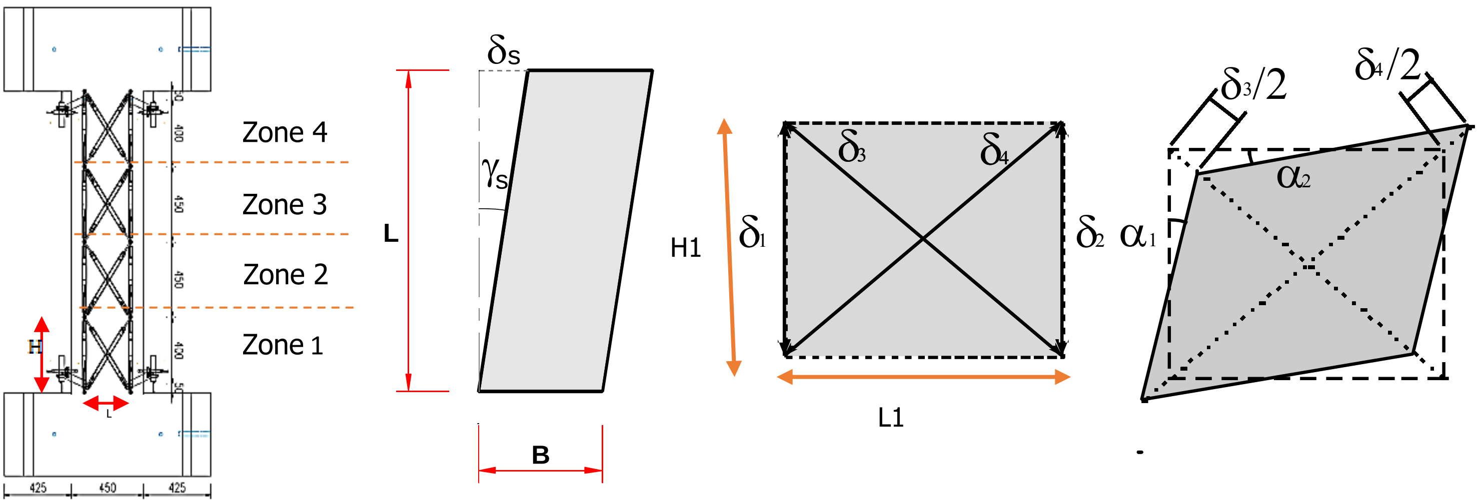
The relationship between shear crack width and shear drift component may be formulated by assuming that the shear deformation is caused by diagonal cracking as shown on Fig. 5. Horizontal (W_{hi}) and vertical (W_{vi}) components of crack in the global X'-Y' axes can be obtained from the crack width (W_{xi}), crack slip (W_{yi}) and gauge inclination angle (θ_i) using Eq. 3. Inclination angles were taken as the angle between the crack gauge and the beam longitudinal axis. Based on these assumptions Eq. 4 is proposed [12].

$$\begin{bmatrix} W_{hi} \\ W_{vi} \end{bmatrix} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i \end{bmatrix} \begin{bmatrix} W_{xi} \\ W_{yi} \end{bmatrix} \quad (3)$$

$$\delta_s = \sum_{i=1}^{n} W_{hi} \quad (4)$$

Where

n: number of shear cracks



(a) Disp. gauge zones (b) Shear deformation (c) Disp. components (for one zone)

Fig. 2 – Shear drift calculation

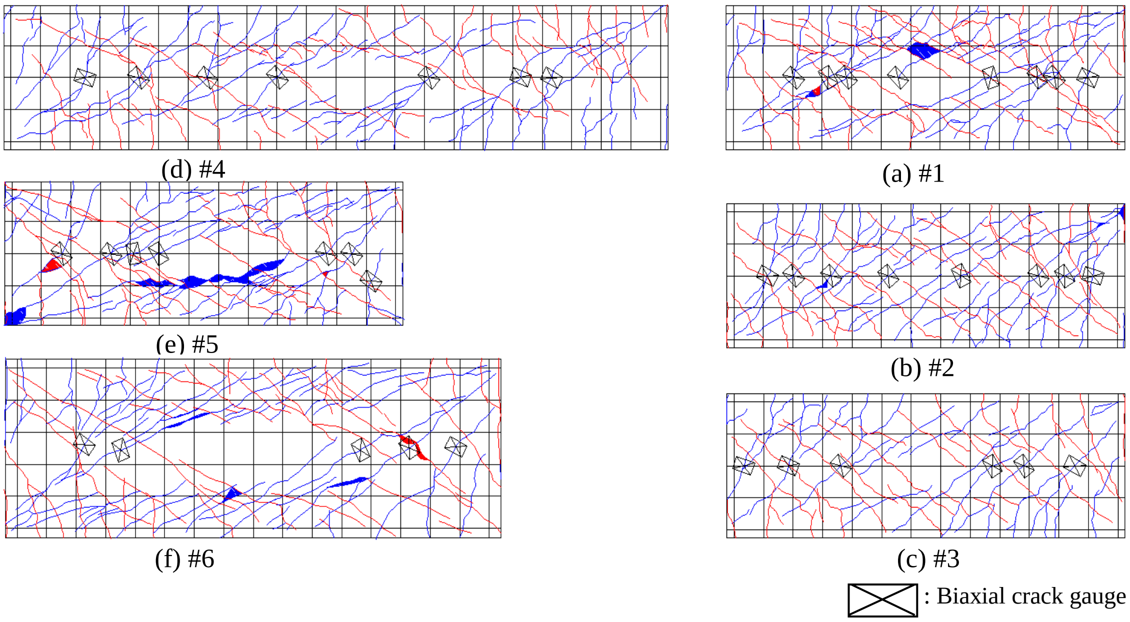


Fig. 3 – Crack patterns and gauge locations at R=2.00%

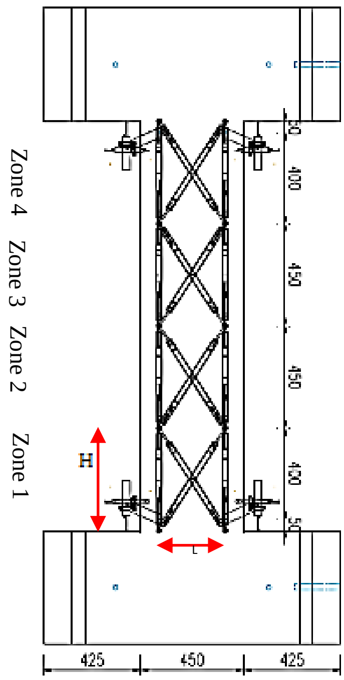


Fig. 4 – Displacement gauges (units in mm)

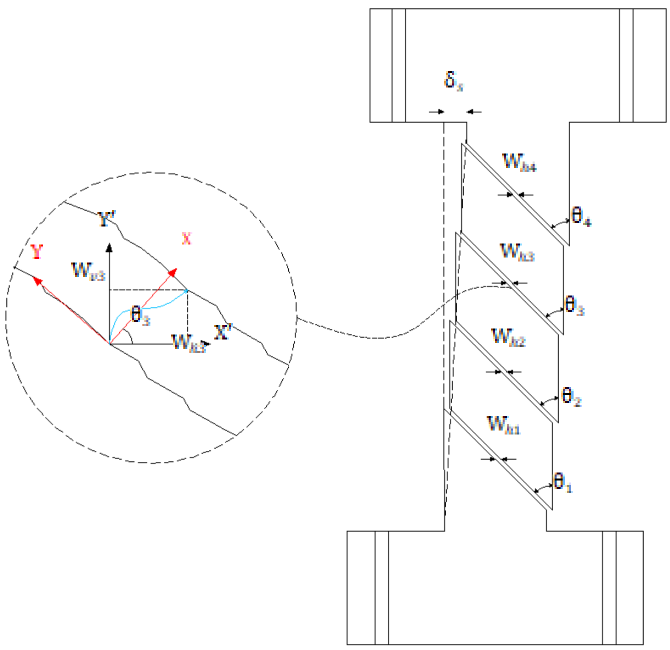


Fig. 5 – Crack in global axis (AIJ 2004 guidelines)

4. Residual crack width and shear drift

The relation between total residual shear drift and transverse crack width can be obtained for each load cycle. This relation was plotted at each load cycle in Fig. 6. The solid blue line represents the experimental results. Linear regression lines were drawn as represented by the red lines for R=0.125%-1.00% and blue broken lines for R=0.125%-2.00%. At R=0.125%-1.00%, the ratio between $\sum_{i=1}^{n} W_{hi}$ and δ_s ranged from 75.6% to 108% for all specimens. The closest result was achieved by #3 with 98% and the lowest was from #5. In the previous study by Kono et al. (2018), the ratio ranged from 52% to 78% at peak drifts for the same six specimens. From these results, it is apparent that the term Eq. 3 total horizontal crack widths and horizontal drift correlate better for residual cracks and drifts than for peak values This could be explained by the sliding at peak drifts of negative cracks, which tends to be wider.

Regression analysis for R=0.125%-2.00% as shown by the blue broken lines on Fig. 6, except for #5 since one of the crack gauges malfunctioned at R=1.50%. The ratio for #1, #2, #3, #4 and #6 ranged from 59% to 82%. From this result, residual crack width agreed with residual drift better for R≤1.00% rather than for R≤2.00%. Total residual crack width was found to be lower than residual drift , and one of the main reasons for this discrepancy at higher drifts could be the negative cracks which were still open during the positive loading cycle. The negative cracks were not measured.

From specimens #1, #2, #3 results, the effect of transverse reinforcement on total residual horizontal crack width can be seen. Spcimen #1 had the lowest transverse reinforcement ratio ($\rho_w = 0.2\%$), meanwhile #3 has the highest ratio ($\rho_w = 1.2\%$). At the same drift, an increase of transverse reinforcement reduced transverse crack width. Specimen #3 had the smallest total horizontal crack width ($\sum_{i=1}^{n} W_{hi}$= 1.43 mm) at R=2.00%. However, there isn't any clear relationship between total residual horizontal crack width and residual shear drift for those three specimens. Unlike the other specimens, the higher shear span ratio specimen #4 showed good agreement between residual crack width and drift all the way up to 2%. In contrast, the specimen with higher f'c (specimen #5) and larger cross-section (specimen #6) showed greater error at 2%. This explained by the spalling areas near to crack gauges as shown in Fig. 3.

Overall, the model based on total residual horizontal crack width was equal to the residual shear drift with good accuracy up to residual drift of 1%.

5. Conclusions

An experimental test was conducted on six RC beams with high strength reinforcement to study the possibility of the prediction of shear drift based on model proposed by AIJ Guidelines 2004. The finding of this study are summarized as follow:

1. The ratio between the total transverse crack width and shear drift for R < 1.00% and R < 2.00% are 76%-108% and 52%-82%, respectively. These results are limited to lateral deformation of RC members failing in shear; application to RC members failing in flexure and bond should be verified.

2. The negative cracks should be considered at higher residual drift, because they were open under the positive loading and contribute to the total residual transverse crack width.

6. Acknowledgements

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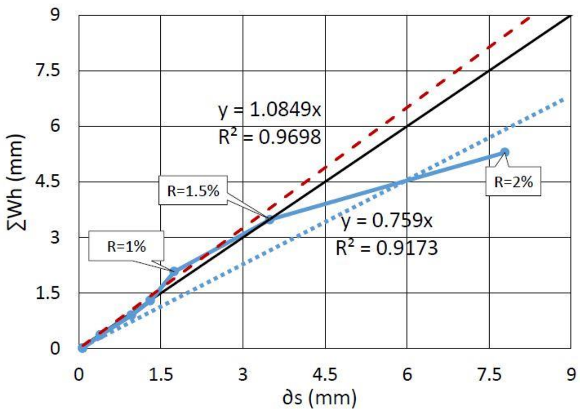
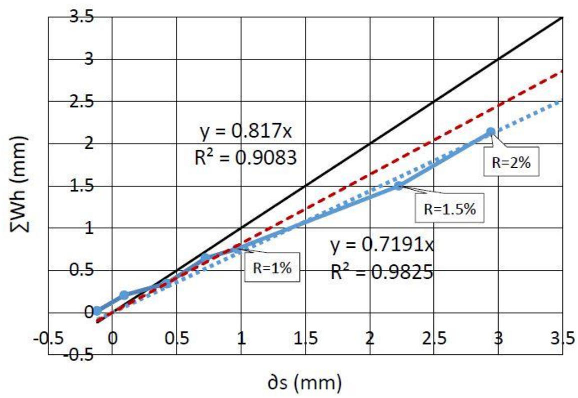
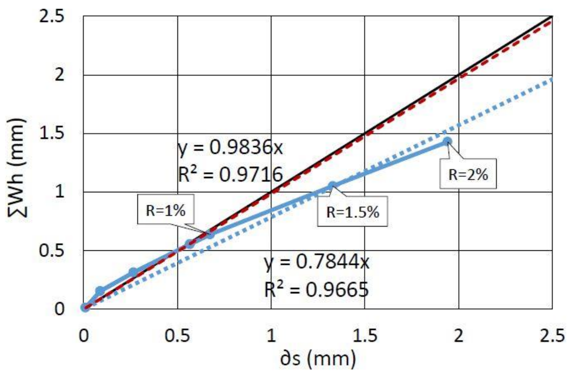


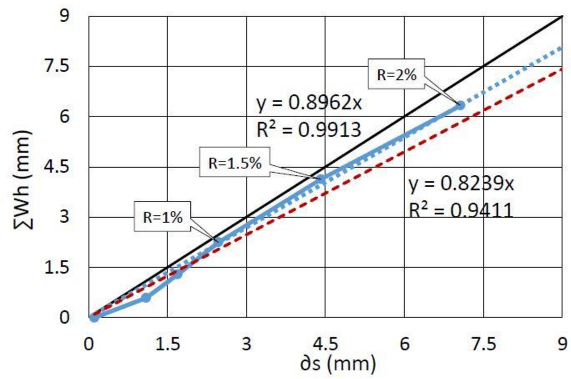
(a) #1 B24-02-SS (control)



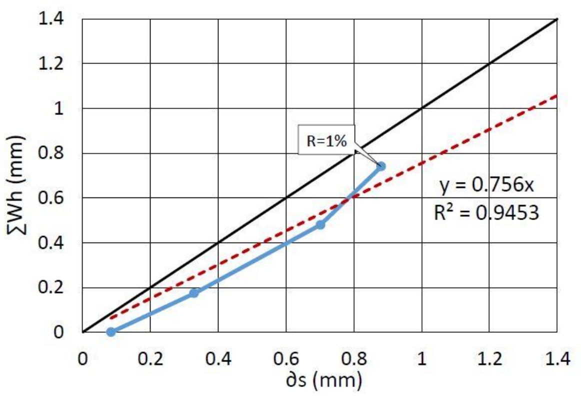
(b) #2 B24-06-SS (higher ρ_w)



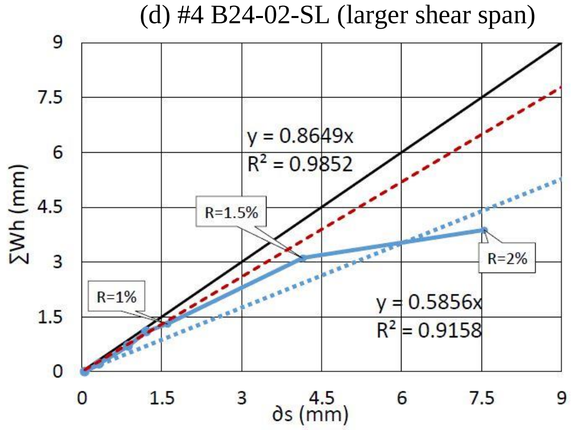
(c) #3 B24-12-SS (highest ρw)



(d) #4 B24-02-SL (larger shear span)



(e) #5 B60-02-SS (higher f'c)



(f) #6 B24-02-XS (larger cross section)

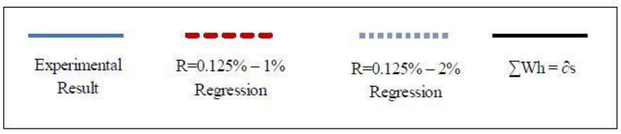


Fig. 6 – Total residual horizontal crack and residual shear drift

6. References

[1] Shin D, Haroon M, Kim C, Lee B S, Lee J Y (2019): Shear Strength Reduction of Large-Scale Reinforced Concrete Beams with High-Strength Stirrups. *ACI Structural Journal*, 116(5).

[2] Munikrishma A (2008): Shear Behavior of Concrete Beam Reinforced with High Performance Steel Shear Reinforcement. master thesis, *North Carolina State University*, Raleigh, NC, 2008, 167 pp.

[3] Munikrishma A, Hosny A, Rizkalla S, Zia P (2011): Behavior of Concrete Beams Reinforced with ASTM A1035 Grade 100 Stirrups under Shear. *ACI Structural Journal*, V. 108, No. 4, pp. 34-41.

[4] Lee J Y, Lee D H, Lee J E, Choi S H (2015): Shear Behavior and Diagonal Crack Width for Reinforced Concrete Beams with High-Strength Shear Reinforcement. *ACI Structural Journal*, 112(3).

[5] Lee J Y, Choi S H, Lee D H (2016): Structural behaviour of reinforced concrete beams with high yield strength stirrups. *Magazine of Concrete Research*, 68(23), 1187-1199.

[6] Oh B, Kang Y J (1987): New Formulas for Maximum Crack Width and Crack Spacing in Reinforced Concrete Flexural Members. *ACI Structural Journal, American Concrete Institute*, 84(10), pp. 103-112.

[7] Kakuta, Y. et al. (1970): Maximum Crack Width of Reinforced Concrete. *Concrete Journal*, *Japan Concrete Institute*, 8(9), pp. 1-10.

[8] Gergely P, Lutz L A (1968): Maximum Crack Width in Reinforced Concrete Flexural Members. *ACI Special 20 Publication, American Concrete Institute*, pp. 87-117

[9] Fukuyama H, Suwada H, Iso M, Matsuzaki Y, Nakano K, Kasahara M (2000): Evaluation of Damage Limit State of RC Element due to Shear Crack Width. *Proceeding of AIJ, Architecture Institute of Japan*, C-2, pp. 13-14.

[10] Shinomiya K, Watanabe F (2002): Study on Prediction of Shear Crack Width for Reinforced Concrete Beams. *Proceeding of AIJ, Architecture Institute of Japan*, C-2, pp. 295-296.

[11] Lumlertlucksanachai N, Kono S (2012): Damage Assessment of Reinforced Concrete Columns with SD685 Shear Reinforcement in Flexure Shear Test: Part 1. Outline of Experiment. *AIJ Annual Convention, Architecture Institute of Japan*, pp. 401-402.

[12] Architecture Institute of Japan (2004): Guidelines for Performance Evaluation of Earthquake Resistant Reinforced Concrete Buildings (Draft). Architectural Institute of Japan.

[13] Kono S, Setiawan J, Obara T, Del Zoppo M, Watanabe H, Mukai D J (2018): Seismic Performance of RC Beams Focusing on Failure Mode and Crack Evaluation. *Proceedings of the 11th National Conf. in Earthquake Engineering, Earthquake Engineering Research Institute*. Los Angeles, CA.

[14] Rinaldi R, Obara T, Kono S, Mukai D J (2018): Relation Between Shear Crack Width and Shear Drift Component in RC Beams with High Strength Transverse Reinforcement. *Summaries of Technical Papers of Annual Meeting*, AIJ.

[15] Rinaldi R, OT, NK, KS (2018): Evaluation of Shear Crack Width from Experiment on Reinforced Concrete Beams. *The 5th Joint Workshop on Building / Civil Engineering between Tongji & Tokyo Tech*, July 26-27, Tokyo Inst of Technology, Japan, pp No.3-3.

[16] Obara T, Setiawan J, Watanabe H, Kono S, Ohmura T (2017): Crack Evaluation of Reinforced Concrete Beams with High Strength Transverse Reinforcement. *Summaries of Technical Papers of Annual Meeting*, AIJ, pp. 3-6.

[17] Architecture Institute of Japan (2015): guidelines for structural design and construction of prestressed concrete building based on performance evaluation concept (Draft). Architectural Institute of Japan.

Yuniarsyah E, Kono S, Tani M, Taleb R, Sugimoto K, Mukai T, (2017): Damage evaluation of lightly reinforced concrete walls in moment resisting frames under seismic loading. *Engineering Structures* 132: 349-371.

