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Predicting the Response of Shear-critical Reinforced Concrete Beams using Response-2000 and SNI 2847:2013

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Abstract: This study investigates the accuracy of Response-2000 in predicting the response of shear-critical reinforced concrete beams. The experimental data selected was that obtained by Vecchio and Shim in 2004 on twelve reinforced concrete beams which sought to replicate beams originally tested by Bresler and Scordelis in the early 1960s. This study also aims to compare the results obtained to the predictions of SNI 2847:2013. It is demonstrated that Response-2000 is capable of providing accurate predictions of load-deflection responses up to the peak load, but underestimates the ductility of beams that exhibit a mixed flexure-shear failure mode. It is also shown that both methods provide conservative predictions of the shear strength of beams with no shear reinforcement, with the software providing more consistent and reliable predictions of shear strength of beams containing shear reinforcement.

Keywords: Analysis; classic beam test; design; Response 2000; SNI 2847:2013; shear.

Introduction

In the design of reinforced concrete beams, practising engineers typically have to design for flexure and shear. Flexural design is generally quite straight forward and involves the design of a number of critical sections in a beam [1]. The classic beam theory incorporating nonlinear stress-strain relations is generally used for this purpose [2,3]. Due to the reliability of the theory, the flexural strength and ductility of a reinforced concrete beam can be predicted with a high degree of accuracy. The simplicity and accuracy of the flexural design allows engineers to ensure that as a reinforced concrete beam begins to fail, the tension steel yields, allowing the beam to undergo noticeable deflection thereby providing an early warning.

Similarly, shear design of a reinforced concrete beam is quite straightforward. However, unlike flexural strength, the shear strength of a beam is difficult to predict with accuracy and is generally not well understood [4,5]. This may put engineers in a difficult position when asked to justify their design results and to explain what is being represented. While flexural design involves the analysis of a single or limited number of critical sections, shear design involves a more complicated, two-dimensional problem dealing with the response of the beam web region over multiple sections.

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Unlike flexural failure, shear failure can occur suddenly and without warning. This is particularly true for reinforced concrete beams containing little or no shear reinforcement, which can lead to a dangerous and undesirable brittle failure mechanism [6].

The collapse of the rigid frame section of the Wilkins Air Force Warehouse in 1955 is perhaps the best example to date to demonstrate the importance of shear [5,7]. To provide additional insights, an example of crack patterns and failure modes of three reinforced concrete beams containing different amounts of shear reinforcement is shown in Figure 1. With regard to the first two beams shown in Figs. 1(a) and (b), it is evident that the beams exhibited only a small measure of ductility before failure ultimately occurred, which was sudden and brittle. In contrast, the beam shown in Fig. 1(c) failed in a ductile manner resulting from yielding of the tension steel (flexural failure). It is clear that flexural failure is a desirable failure mechanism and that shear failure must be avoided – should a beam fail at all.

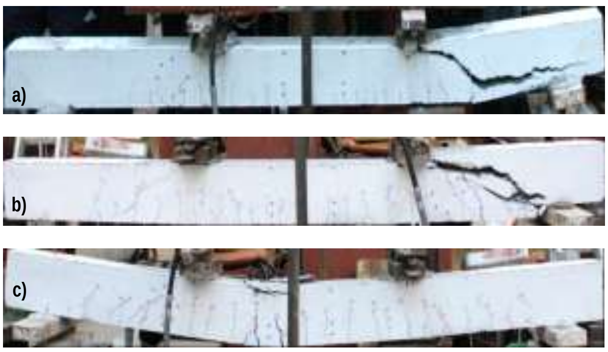


Figure 1. (a) Shear failure in a reinforced concrete beam containing no shear reinforcement; (b) shear failure in a reinforced concrete beam with improper shear detailing; and (c) typical flexural failure. Note the large residual deflection sustained by the beam shown at the bottom

To provide insights into the response of shear-critical reinforced concrete beams, this study presents an assessment of the response of such beams to an established theory called the Modified Compression Field Theory (MCFT) [8] by using a simplified sectional analysis software package called Response-2000 [9]. This software package was selected as it is capable of predicting not only the shear strength, but also the full load-deflection response of reinforced concrete beams/columns subject to combined moment, shear and axial loading. It is expected that the findings of this study will be beneficial to structural engineers who require a deeper understanding of the response of reinforced concrete beams at risk of failing in shear and those who want to check their day-to-day beam designs using a simple yet reliable tool and within a reasonable timeframe. This approach could complement global structural analysis (e.g. [10] and [11]) by providing engineers with a more detailed assessment on the response of critical structural elements with unusual detailing or ordinary elements subjected to unforeseen loading. Findings are also expected to provide initial insights into the accuracy of the shear design procedures described in SNI 2847:2013 [12].

Analysis Study

In 2004, Vecchio and Shim undertook laboratory tests on twelve reinforced concrete beams which replicated the tests originally carried out by Bresler and Scordelis in the early 1960s [6,13]. The tests aimed to check the repeatability of the original experiments, with respect to the load capacities and failure modes, and to investigate the post-peak response which was not explored in the original experiment.

The schematic of the beam geometry and steel reinforcement is shown in Figure 2, whereas the beam cross-section details are presented in Figure 3. Four series of beams were tested: OA series containing no transverse reinforcement and A-, B-, and C-series all containing transverse reinforcement. This coding is followed by a number suffix to indicate the three different beam spans: 1, 2, and 3 which, respectively, represent beams of short (3.7 m), intermediate (4.6 m) and long (6.4 m) span. All beams had the same depth (552 mm). Table 1 lists the reinforcing bars used in the beam tests. It was not clear whether the 25-mm longitudinal reinforcement bars in Beams C2 and C3 have the properties of M25[a] or M25[b]. In this study, the properties of M25[a] (25 mm) were used. Furthermore, it was assumed that the diameter for bar D4 is 5.7 mm rather than 3.7 mm as stated in the original paper. The concrete compressive strengths for series 1, 2, 3 beams were 22.6, 25.9, and 43.5 MPa, respectively. It was noted that steel plates with dimensions of 150×300×58 mm and 150×350×20 mm were used throughout the tests for the loading and support plates, respectively.

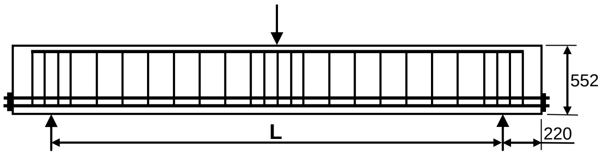


Figure 2. Vecchio and Shim's Beam Geometry and Reinforcement Layout. For more detailed information about the test set-up, refer to [13].

Table 1. Properties of Reinforcing Steels [13].

Bar ID	Diameter mm	Area mm^2	f_y MPa	f_u MPa	E_s GPa
M10	11.3	100	315	460	200
M25[a]	25.2	500	440	615	210
M25[b]	25.2	500	445	680	220
M30	29.9	700	436	700	200
D4	5.7*	25.7	600	651	200
D5	6.4	32.3	600	649	200

*assumed.

The tests showed that in all beams containing no transverse reinforcement (Beams OA1, OA2, and OA3), failure was sudden with no ductility beyond the peak load. In beams of short and intermediate spans containing shear reinforcement (Beams A1, A2, B1, B2, C1, and C2), the response was characterized as shear-flexure in nature. Final failure occurred due to crushing of the concrete in the compression zone. In the longest spanning beams (Beams A3, B3, and C3), failure occurred by crushing of the concrete which first appeared directly beneath the loading plate. The failure mechanism can be categorized as a flexure-compression in nature. Diagonal cracking was minor. For more detailed information, one shall refer to Vecchio and Shim [13].

Response 2000

Response-2000 is a sectional analysis program capable of predicting the complete load-deformation response of reinforced concrete beams/columns [9]. This program treats a beam/column cross-section as a stack of membranes on which the response is assumed to follow the MCFT [8,9]. This program assumes that plane sections across the depth of the member remain plane and no significant transverse clamping stress develops. The former assumption implies that the program should only be used when the assumptions of classical beam theory are valid. Regarding the latter assumption, this is reasonably valid when the critical section is at a sufficient distance from the supports and points of load application (e.g. at a distance greater than the effective depth of the member), which is a reasonable assumption for large size members. The unique feature of this sectional analysis program concerns the consideration of shear, allowing one to consider the combined influence of shear, flexural and axial forces. The program can be downloaded for free at www.ecf.utoronto.ca/~bentz/r2k.htm [14].

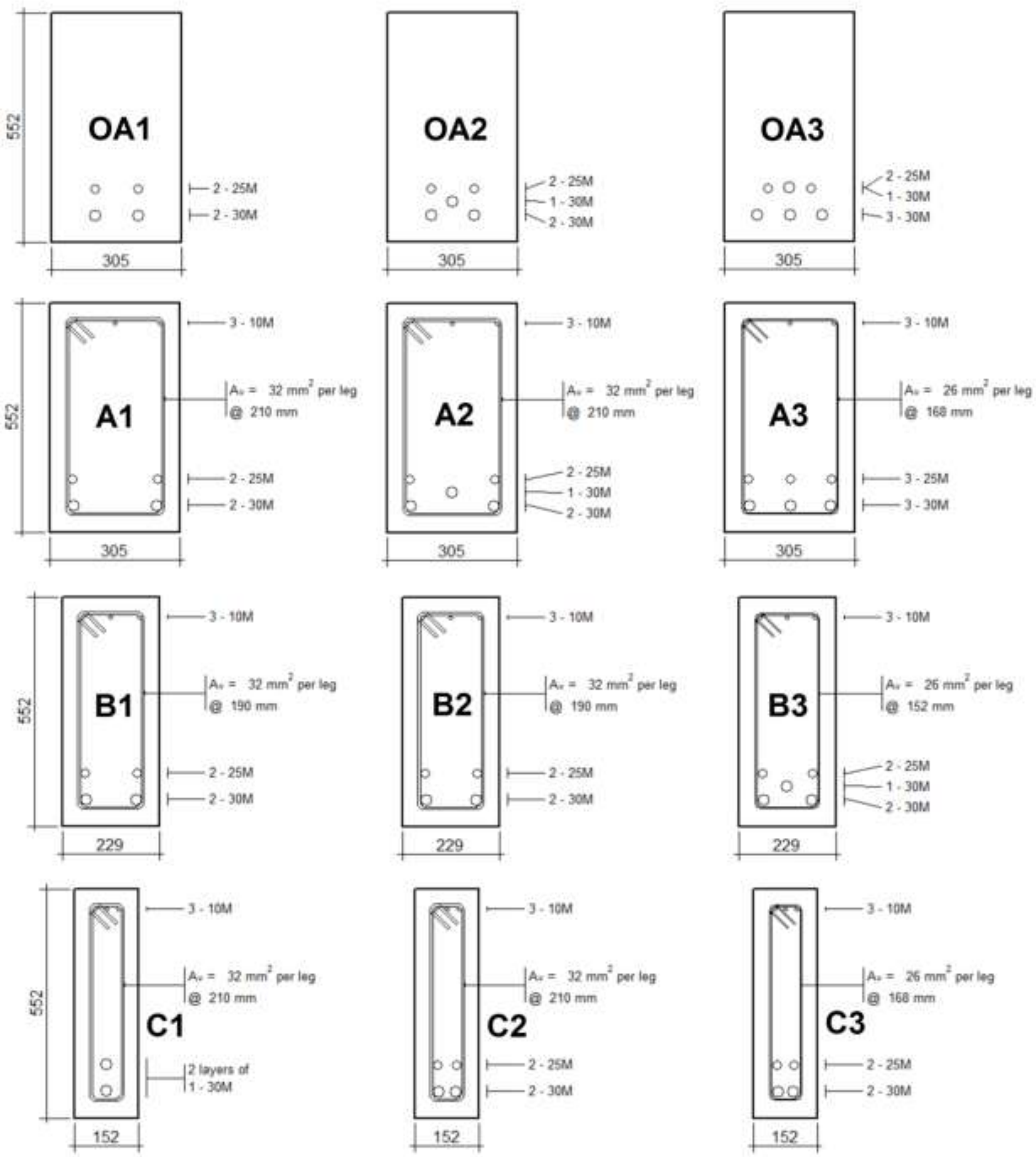
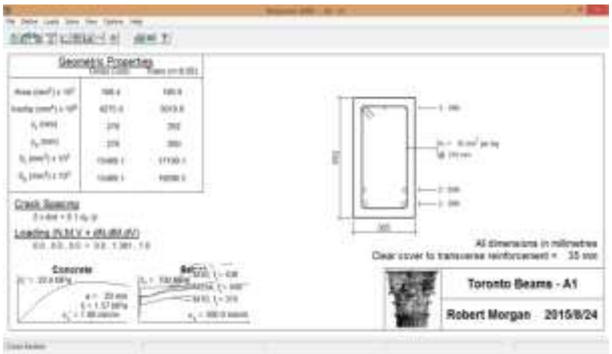


Figure 3. Cross-section Details of Vecchio and Shim Beams [13]. This Schematic Diagram was Prepared using Response-2000 Software [9].

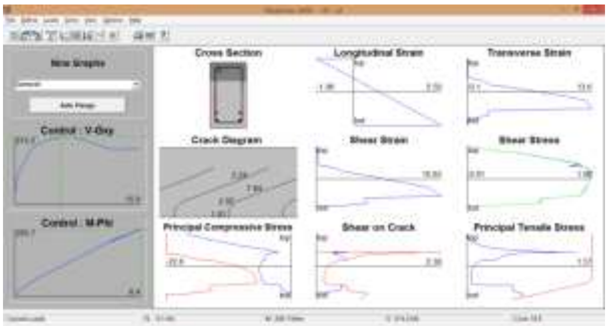
Response-2000 has a user-friendly interface, allowing users to quickly define the geometrical and mechanical properties of a beam under study and input the details of reinforcement and load configuration within a short time. Figure 4 shows an example of input data for Beam A1. The time required for preparing similar input data is less than 30 minutes on average. It then takes less than 5 seconds to perform the sectional and full member analyses, with an Intel® Core™ i5-4200U 2.3GHz computer with 4GB memory.

Standard National Indonesia (SNI 2847:2013)

The SNI 2847:2013 is the building standard used in Indonesia for structural design of concrete structures [12]. This standard supersedes the SNI 03-2847-1992 [15] and has become the mandatory code of practice for design and construction of reinforced concrete buildings in Indonesia. The standards have adopted the requirements specified in the ACI 318M-11[16].



(a)



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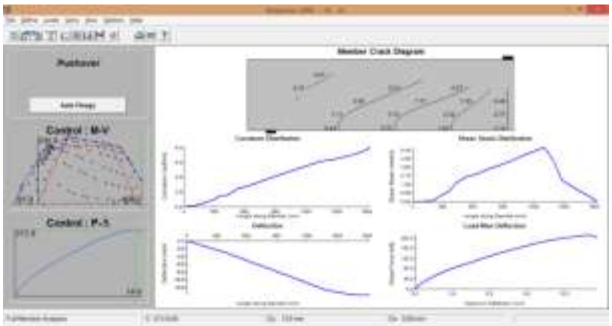

(c)

Figure 4. Screenshots of: (a) The Main Response-2000 Terminal Displaying a Summary of All Input Data for Beam A1; (b) The Sectional Response Output Plots; and (c) The Member Response Output Plots.

In this standard specification, the nominal shear strength of a one-way linear member is calculated from the sum of the nominal shear strength provided by the concrete and the nominal shear strength provided by the shear reinforcement. For a non-prestressed member subjected to no axial force, the concrete contribution (V_c) can be taken as the least of:

$$V_c = \left(0.16\lambda\sqrt{f_c^{'}} + 17\rho_w \frac{V_u d}{M_u}\right) b_w d \tag{1}$$

$$V_c = 0.29\lambda\sqrt{f_c^{'}} b_w d \tag{2}$$

where V_c is the nominal concrete shear strength, λ is a reduction factor for lightweight concrete, f_c' is the concrete compressive strength, ρ_w is the tension reinforcement ratio, V_u and M_u are the factored shear force and moment at a section respectively, d is the effective depth, and b_w is the width of beam web. In this equation, there are three main parameters: $\lambda\sqrt{f_c^{'}}$, ρ_w, and $\frac{V_u d}{M_u} \leq 1.0$. $\lambda\sqrt{f_c^{'}}$ is a parameter associated with concrete tensile strength in the web region. This parameter shall be taken as no greater than 8.3 MPa unless minimum web reinforcement has been provided in accordance with SNI 2847:2013 Sections 11.4.6.3, 11.4.6.4 or 11.5.5.2. If the level of the pre-stressed force is insignificant and torsional effects can be neglected, the minimum web reinforcement shall be taken in accordance with Section 11.4.6.3 as:

$$A_{v,min} = 0.062\sqrt{f_c^{'}} \frac{b_w s}{f_{yt}} \geq 0.35 \frac{b_w s}{f_{yt}} \tag{3}$$

ρ_w is the longitudinal reinforcement ratio, $\frac{A_s}{b_w d}$, which was found to affect shear strength [16]. $\frac{V_u d}{M_u}$ is the shear span-to-depth ratio and shall be taken as no greater than 1.0 (Section 11.2.2.1), in order to limit the value of V_c near a point of inflection.

Results and Discussion

Beam B2

For illustrative purposes, the predicted responses of Beam B2 are presented in Figures 5(a)-(e). Figures 5(a)-(c) present the predicted curvature, deflection and shear strain profiles over the half span of the beam at different stages of loading. It is clear that, as expected, these parameters increase as the load increases. It is evident that the curvature is nonlinear due to concrete cracking and the shear strain is predicted to be at its maximum at a distance approximately equal to the effective depth of the member from the point of load application. For clarity, the predicted load-deflection response and the corresponding crack patterns at selected loading stages are presented in Figures 5(d) and (e), respectively. It is also evident from Fig. 5(d) that the beam response can be divided into three main regions: (i) an initial region where the response remains linear; (ii) a transitional region where the response is highly nonlinear, which occurs primarily due to the formation and propagation of flexural cracks; and (iii) a final somewhat linear response with increasing load until the beam reaches the ultimate strength. During the nonlinear response (Region 2), most of the flexural cracks are predicted to develop between Loading Stages 1 and 5. These cracks then propagate upward and increase in width

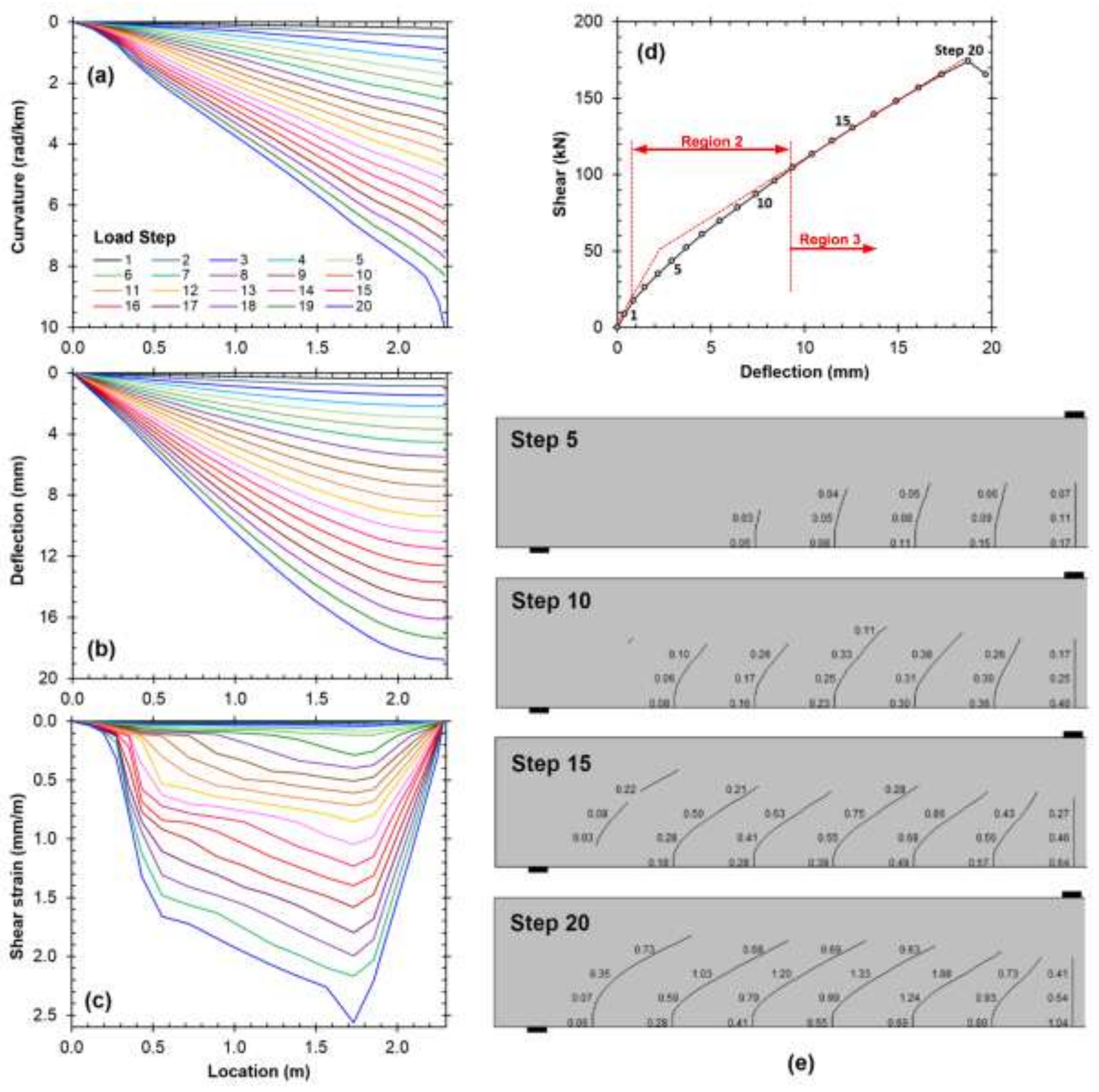

Figure 5. Typical Member Response Outputs: (a) Curvature Over Half of the Beam Span; (b) The Corresponding Deflection Profile; (c) Shear Strain Distribution; (d) Load versus Deflection Response; and (e) Crack Patterns.

during the subsequent loading stages. All cracks appear to have fully formed at Loading Stage 10. Between Loading Stages 10 and 15, it appears that the flexural cracks open further and new diagonal cracks form close to the load point and support. At the peak load (Loading Stage 20), the critical diagonal shear crack is predicted to have a crack width of 1.9 mm which compares reasonably well to the crack width found experimentally.

All Beams

To check the accuracy of Response-2000, Figure 6 presents the predicted response of all beams. Each row presents the response of beams with notionally identical geometry and span, but with different reinforcement arrangements. The first row presents the results of beams with no transverse reinforcement, which is then followed by the results of those with transverse reinforcement. The first, second and third columns present the results of the 3.7 m, 4.6 m, and 6.4 m long beams, respectively. The experimental data are presented at selected points only for comparative purposes; for full load-deflection response, please refer to Vecchio and Shim [13]. Also included in the Figures are the predicted shear capacities according to SNI 2847:2013. The predicted crack patterns are shown in Figure 7, with the half span crack diagrams mirrored to enhance presentation. The predicted crack diagrams are in agreement with the experimental crack patterns reported in Vecchio and Shim [13].

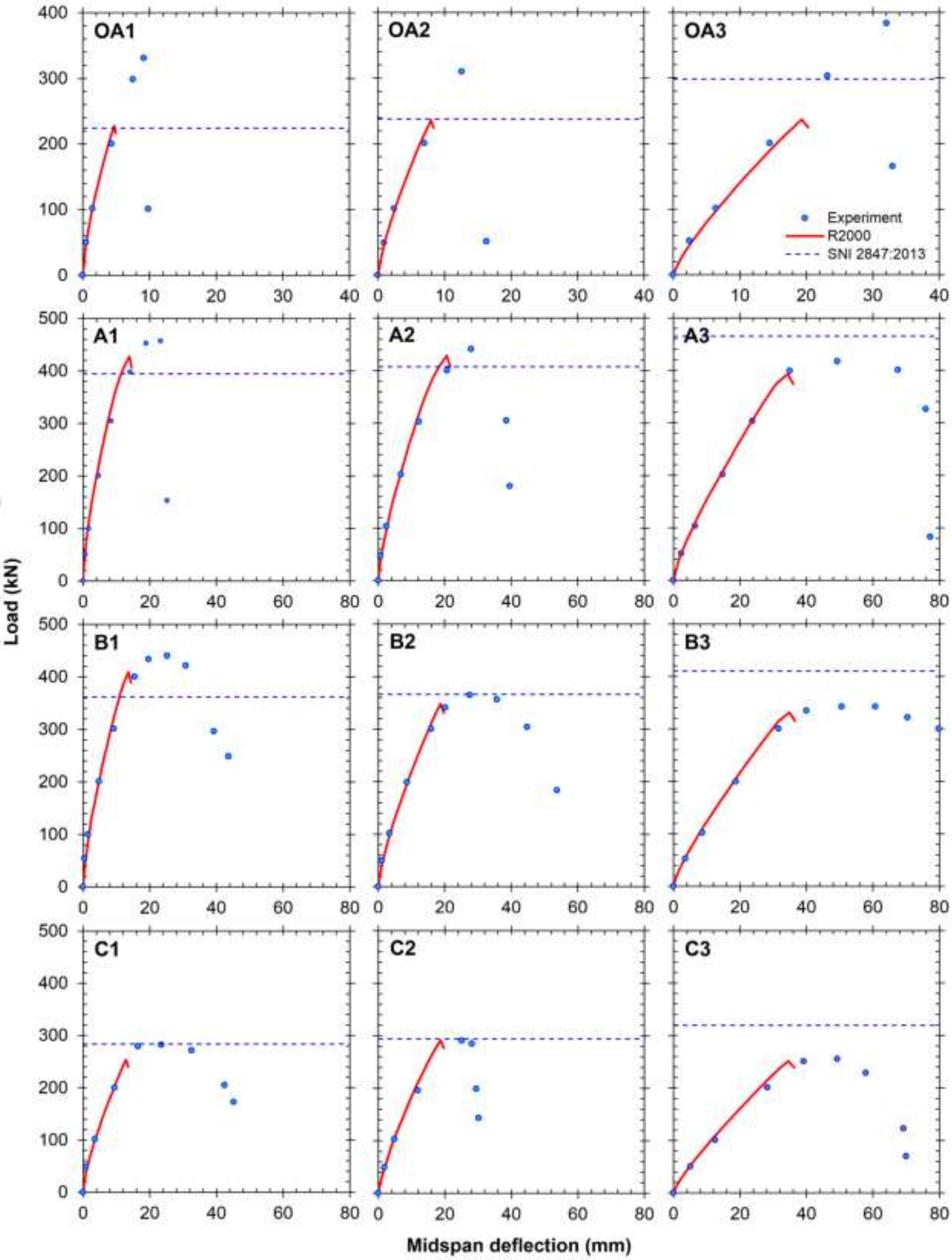

Figure 6. Comparison of Simulated and Observed Load-deflection Response of Twelve Reinforced Concrete Beams Tested under Three-point Loading by Vecchio and Shim [13]. For Full Load-deflection Response, One Shall Refer to Vecchio and Shim's Work [13].

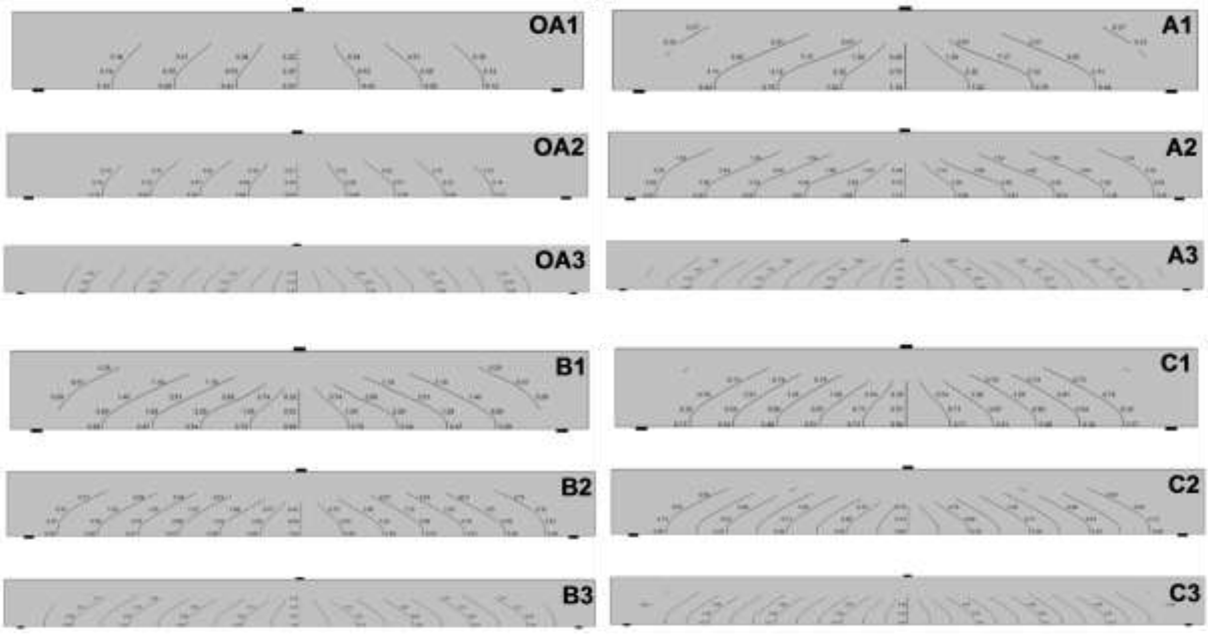

Figure 7. Predicted Crack Patterns

With regard to the Response-2000 predictions shown in Figure 6, it is evident that in general, the predicted responses closely replicate the experimental responses. Each beam is predicted to exhibit an initial linear-elastic response, which is then followed by a transitional nonlinear response and a final somewhat linear response until the peak load. This agreement is indeed impressive considering the complexity of the actual response resulting from the formation of concrete cracks and the propagation of pre-existing cracks thereby decreasing the overall stiffness of the beam.

With reference to the response of beams without web reinforcement (Beams OA1, OA2, and OA3; Figure 6(a)-(c)), it is evident that Response-2000 underestimates the actual beam capacity quite significantly. This can be attributed to the fact that the response of these beams is mainly governed by diagonal tension failure. The actual failure occurred due to rapid propagation of the diagonal crack along the top layer of tension steel to the end of the beam [13] similar to that presented earlier in Fig. 1(a). This localized crack behavior departs from the condition on which the material models incorporated in the program were derived, thereby leading to the inaccuracy. For this reason, Vecchio proposed the residual tension concept [18] and the crack-shear slip formulation [19,20].

Comparing the predicted and observed response of other beams with web reinforcement (Beams A1-A3, B1-B3, and C1-C3; see Figures 6(d)-(l)), it can be seen that the Response-2000 program is capable of providing reasonable predictions of the load-deflection responses of the beams up to the peak load. However, the response near the peak is not well reproduced. In particular, Response-2000 tends to under-estimate the ductility of the longer beams (Beams A3, B3, and C3). Nevertheless, as far as the prediction of load capacity is concerned (e.g. as required from the design point of view), this is still acceptable.

From the results presented in Figures 6(a)-(l), a comparison can also be made to the accuracy of SNI 2847:2013. For ease of observation, Figure 8 provides a summary of all predictions. It was assumed in the analysis that only the 'failed volume' of the beam contributed to the beam self-weight (for simplicity, this was taken as a half the self-weight). As can be seen, the SNI design code tends to underestimate the load-capacity of beams with no transverse reinforcement (Beams OA1, OA2, and OA3). The average of the predicted-to-observed shear capacity ratio for the code is 0.73 and the coefficient of variation (CoV) is 6.9%. This compares favorably to Response-2000 prediction ratios which have a mean of 0.68 and a CoV of 9.2%, indicating that both methods are conservative.

In beams with transverse reinforcement, the average ratio of predicted-to-observed shear strength for SNI 2847:2013 and Response-2000 are 1.02 and 0.96, with CoV values of 14.1% and 5.7%, respectively. While both predictions show a mean value close to 1.0, the code prediction shows higher CoV which indicates greater margin of error. The main limitation of the code prediction can be particularly seen from the over-estimated load-capacity of the long-span beams (Beams A3, B3, and C3). An explanation as to the cause of this discrepancy warrants further investigation. Further research will also be carried out to use Response-2000 to study factors that influence shear strength.

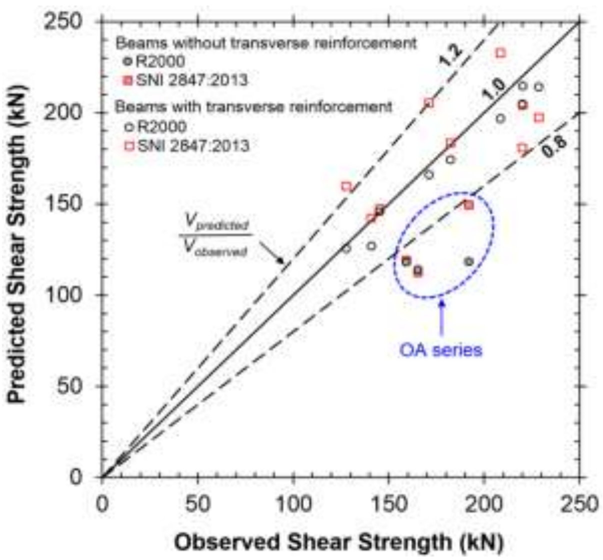

Figure 8. Summary of the Predicted and Observed Shear Strengths

Conclusions

The following conclusions can be drawn from the work presented:

1. From this limited study, it is shown that both Response-2000 and SNI 2847:2013 provide conservative predictions of the shear strength of reinforced concrete beams with no transverse reinforcement. The SNI design code shows an average predicted-to-observed shear strength ratio of 0.73 and a CoV of 6.9%, which is broadly similar to a mean of 0.68 and a CoV of 9.2% obtained from Response-2000.
2. An improvement in accuracy is found for beams containing transverse reinforcement. The code predictions are found to have an average predicted-to-observed shear strength ratio of 1.02 and a CoV of 14.1%. The Response-2000 demonstrates a similar accuracy, with an average of 0.96, but shows a much smaller margin of error with a CoV of 5.7%.
3. It is demonstrated that Response-2000 is capable in providing accurate predictions of load-deflection responses of shear-critical concrete beams up to the peak load. From the majority of the beams under study, however, it is found that the ductility of the beams is generally underestimated, particularly in beams of longer spans having greater longitudinal reinforcement ratios.
4. Response-2000 program is found to be a quick and reliable analysis tool for determining the shear strength, load-deformation response and failure mode of reinforced concrete beams containing shear reinforcement. However, it should be noted that it remains the responsibility of the structural engineer to interpret the post-processing output and design the structural element in question.

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