Response-2000

Load-Deformation Response of Reinforced Concrete Sections

by Evan C. Bentz and Michael P. Collins

Table of Contents

Introduction

Response-2000 is a Windows based computer program which is designed to predict the load-deformation response of reinforced concrete sections subjected to bending moments, axial loads and shear forces. The analytical procedures in Response-2000 are based on traditional engineering beam theory, which assumes that plane sections remain plane and that the distribution of shear stresses across the section is defined by the rate of change of flexural stresses. When relating stresses and strains at various locations across the section, the program uses the Modified Compression Field Theory (Vecchio and Collins, ACI Journal March-April 1986).

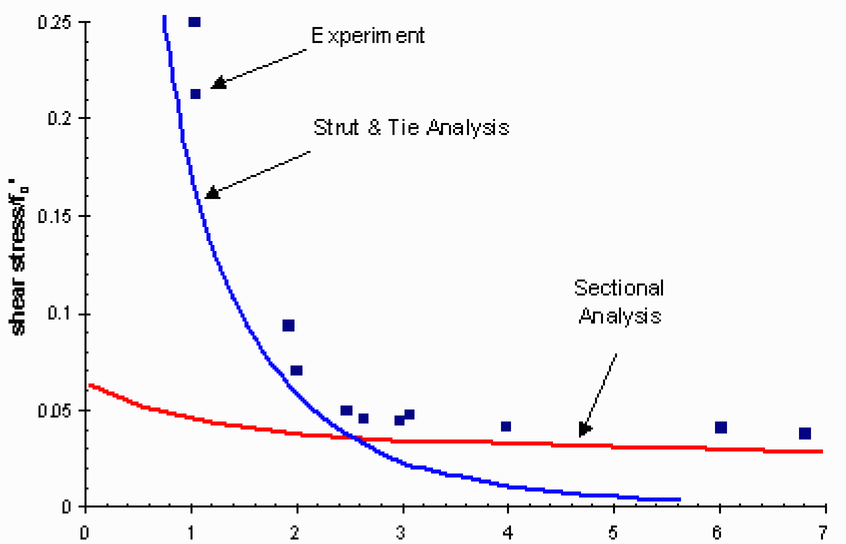
Note that this report was based on version 0.7.5 of Response which is a little older and less stable than the current version. All that's explained here is still true though the final numbers produced with the new version may be slightly different.

Applicability of Sectional Analysis

Engineering beam theory assumes that the response of a particular section depends only on the sectional properties and the values of the applied stress resultants (i.e. the moment, the axial load and the shear). That is, the theory ignores the influence of the details of how the forces are introduced into the member. St. Venant's Principle implies that treating only the stress resultants will be appropriate for sections which are at least the depth of the member away from point loads or supports. Schlaich (PCI Journal, May-June 1987) introduced the terminology of B-regions and D-regions. A B-region is a portion of a member where the assumptions of engineering beam theory are accurate, while a D-region is a portion where the stress distributions are disturbed by the local effects of the applied loads, the supports, or other discontinuities. Sectional analysis is accurate in B-regions but not in D-regions. For disturbed regions it is appropriate to use methods such as strut-and-tie models or non-linear finite element analysis which more closely approximate the actual flow of forces.

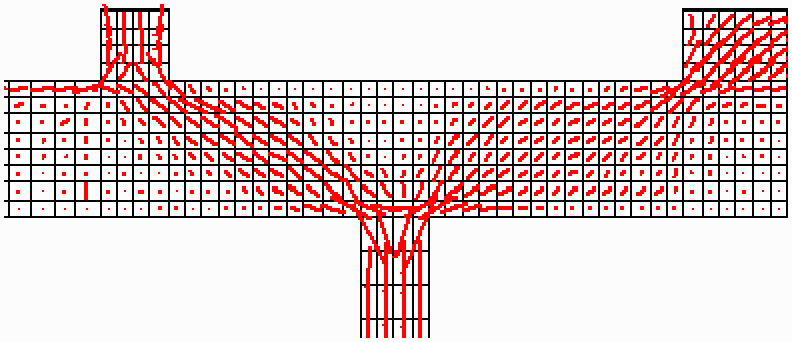
Figure 1 (from Prestressed Concrete Structures by Collins and Mitchell, p 433) shows the results of tests done by Kani on 24 inch deep beams in simple four point loading but with different shear spans. The dots are the experimental results and the two lines are predictions based on different methods. The red line is the prediction based on a sectional analysis tool like Response-2000. The blue line is the prediction based on a strut & tie analysis. Note that when the ratio of the shear span a to the effective depth, d, was less than about 2.5, the sectional model becomes increasingly poor at predicting the strength of the section. For these beams, a finite element analysis or a strut & tie analysis is more appropriate. The sectional analysis is, however, conservative.

Figure 1: Kani Shear Tests: Shear Strength vs a/d Ratio



To explore the reasons for this behaviour, consider Fig. 2. It contains the results from a non-linear finite element analysis of a continuous reinforced concrete transfer girder. It is supported by a column at the centre, and loaded by a column at the left and a wall stub at the right. The short shear span on the left has a clear shear span to total depth ratio of about 1.4, while for the right this ratio is about 1.9. Based on the previous figure, it might be expected that the shear spans should be in a range where there is a transition from sectional behaviour to direct strut behaviour. This can be seen in the red lines which represent the compressive strains in the concrete. On the left side, the lines make a continuous "strut" from the load point to the column with large "shadow" areas below the load point and above the column. On the right, the strains can be seen to be fanning out more, but still with some shadows. Near the centre of the right span, the shadows don't interact and the strains cover the majority of the section. It is in regions like the centre of the right shear span where sectional models excel.

Figure 2: Principal compressive strain trajectories in a transfer girder.



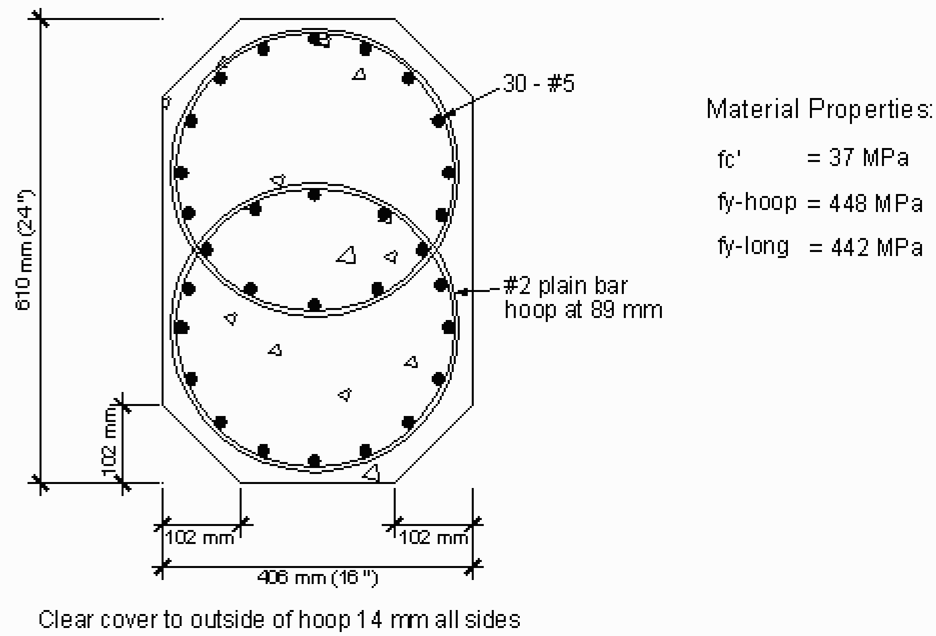
Note also from the Fig. 2 the shadows below the load points. In these regions the distribution of shear stresses isn't yet in a sectional mode. As such, it isn't appropriate to do a sectional shear analysis here. It is wiser to do the analysis for shear strength at a point into the member where the stresses have had a chance to fan out. A reasonable distance to go out is the shear depth, dv, which can be taken as 0.9 times the effective depth, d.

In summary, for beams with shear spans between point loads and supports of less than about 2.5 times the effective beam depth or clear spans of less than about 2 times the total beam depth, the sectional model Response-2000 can be expected to give very conservative results. Additionally, while the shear and moment diagram are maximum under the point load, it is appropriate to do the sectional analysis for shear at a distance dv away from the point of load application. Of course it will still be necessary to check flexure under the load as well, but this can be done with shear turned off in Response-2000.

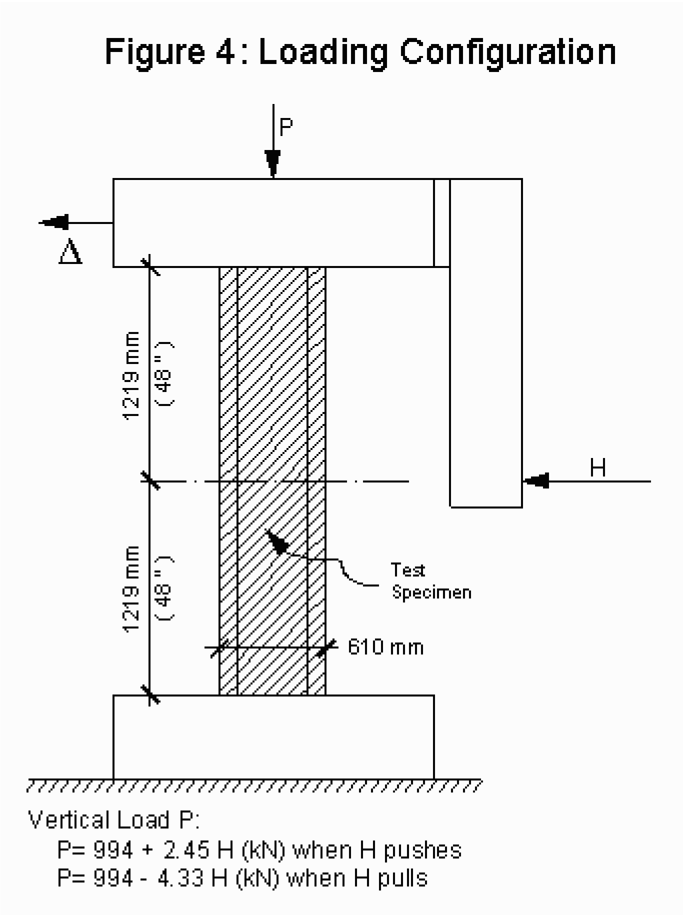
Example Section

A relatively new type of bridge pier used in California involves the use of two interlocking spirals as shown in Fig. 3. This reinforcement configuration provides efficient confinement for a column with a "rectangular" section. However, calculating the shear strength of such a column from, say, the ACI shear equations is not a straightforward task. To answer some of the questions about the shear behaviour of such columns, a series of tests were conducted in 1995 at the University of California, San Diego by Nigel Priestley and Gianmario Benzoni. The results of one of these tests, Inter-4, will be used to introduce the capabilities of Response-2000.

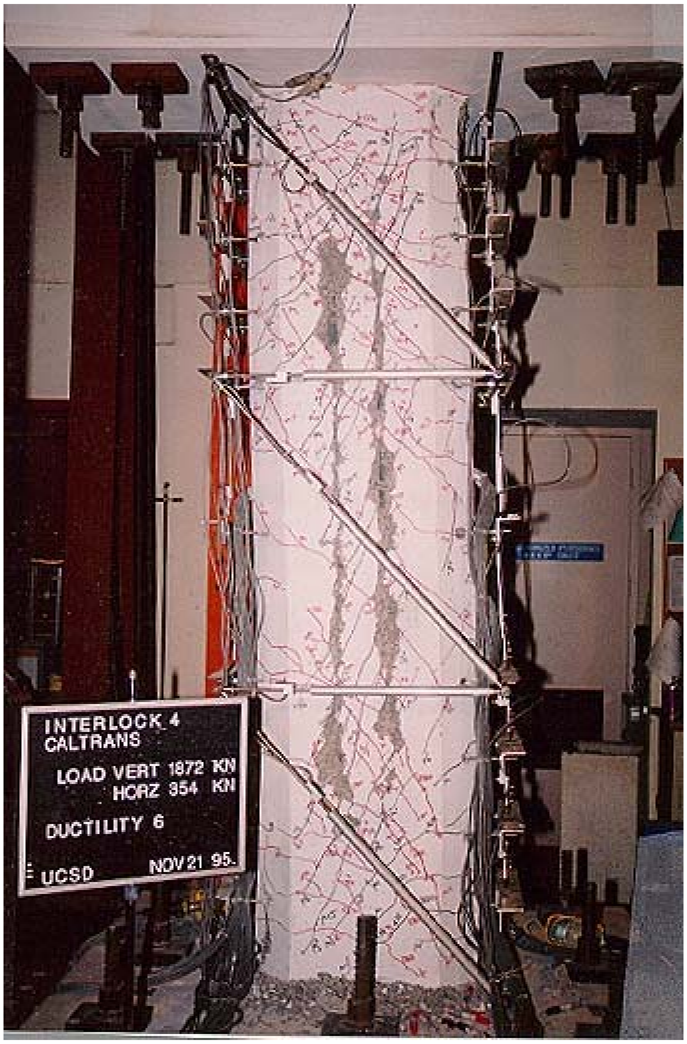
Figure 3: Geometry of Section
UCSD Inter-4



A schematic view of the test set up is shown in Fig. 4. The loading is applied so that the column is subjected to a constant shear over the height of the column and moments which are highest at the ends of the column and are zero at mid height. The axial force regime is representative of that experienced by one pier of a two pier bent during an earthquake. The axial compression due to the gravity loads is 994 kN. As the lateral force, H, pushes, the compression in the column increases by 2.45 x H. When the lateral force pulls, the compression decreases by 4.33 x H. Thus the axial load becomes tensile when the pull load exceeds 218 kN.



The appearance of the test specimen near the end of the testing is shown in Fig. 5. Note that the ends of the column shown no obvious signs of flexural failure. The failure involved two symmetrical longitudinal zones of distress located about 75 mm on each side of the middle line of the column. Can we explain this particular type of shear failure?



Entering the Cross Section into Response-2000

To install Response-2000, select the "download" section of this web site and follow the instructions there as well as in the "help" section of this site. Once downloaded, start the program.

To make a new cross section, select the "Define | Quick Define" menu choice. This will start a "wizard" that will assist in creation of the cross section. The first of four pages will appear asking for information.

In the first window, enter a title of "UCSD Inter-4" (without typing the quotes, of course). For the second box (press tab or click with the mouse to get to that box), enter your own initials. Response-2000 currently defaults to SI metric units, though US customary units as well as the traditional metric units of kg and cm are also available under the "options" menu. For the concrete cylinder strength, enter 37 MPa. Note that the units are already shown. For the longitudinal steel yield value, enter 442 MPa and for the transverse yield, enter 448 MPa. Click on the "Next" button to go to the next window of the wizard. Note that you can return to previous pages with the "back" button as well.

The second window allows selection of the concrete cross section. Listed are a number of common sections such as rectangles, circles, I beams, as well as some more exotic ones such as ellipses and hollow columns. Response-2000 also contains standard AASHTO sections amongst others in a different part of the program. Second from the bottom of the list is what we want. Pressing the tab key at this stage will move the highlight section over to the first location for entry of the geometry. Note that the bottom of the window shows a short description of what is needed. The top term here is the total section width which is 406 mm. The overall height was 610 mm, and the width at top and bottom extremes was 202 mm (406-102-102 mm). Pressing the Next button will go to the next screen.

The third window asks for longitudinal steel information first for the top hoop of the specimen and second for the bottom. The specimen had a total of 30 longitudinal bars, so select 15 for the number of bars for the top. Response-2000 allows for bars to be entered by cross sectional area or by designation. Loaded into the program at startup are over 100 different bar titles, such as #8, 25M as used in Canada, JD25 for Japanese deformed 25 mm bars, etc. In this case, US #5 bars are needed which Response-2000 designates as #5. As such, press tab twice to skip the option of selecting by area and instead type in "#5" (no quotes) as the bar designation. Note that the information for the bottom hoop has been automatically selected to be the same as the top, so pressing the "next" button is all that is left here.

The final window is for transverse reinforcement and prestressing tendons, if any. Interlocking hoops have automatically been selected as the transverse type, so press tab twice to get to the bar type selection. Here the bars were US #2 bars (0.25 inch diameter). The spacing was 89 mm, so enter that in the next box, and the clear cover was 14 mm. In Response-2000, clear cover indicates the distance from the outside of the specimen to the nearest steel, be it transverse steel or longitudinal steel. As there are no tendons, press the "Finish" button to finish.

Automatic Cross Section Plot from Response-2000

After closing the wizard, the cross section of the column (or beam) will have been automatically drawn by Response-2000. This is reproduced here as Fig. 6. As with all Windows programs, any screen can be printed by selecting the "File | Print" Option.

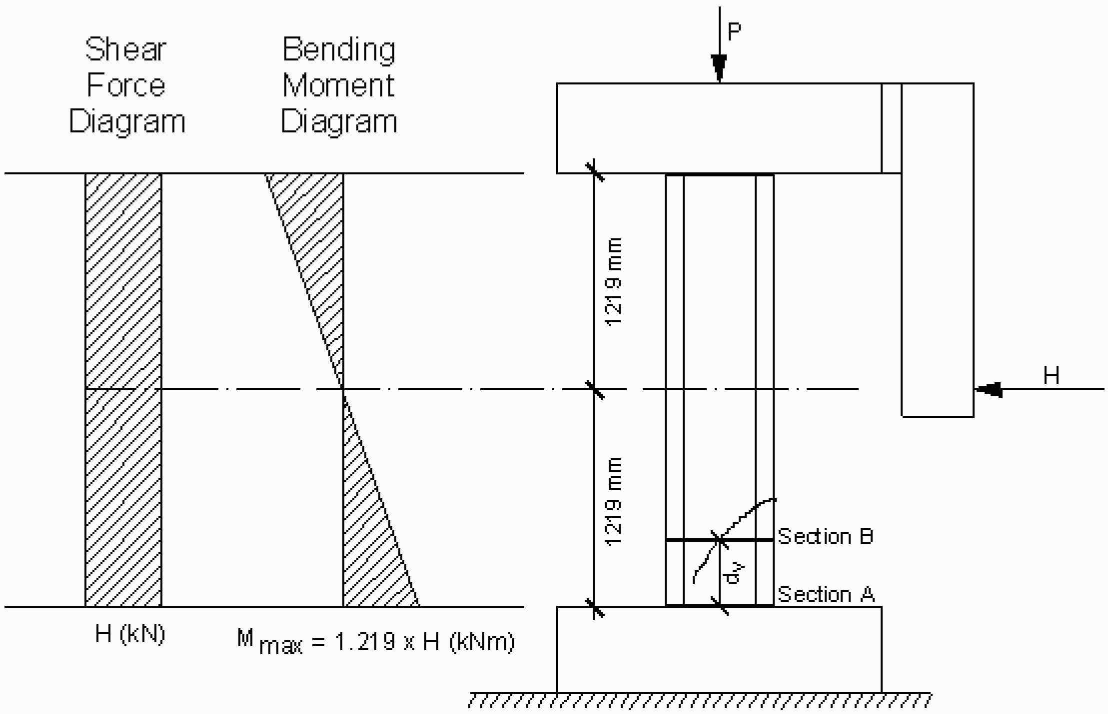
The point of including such a screen is to permit easy checking of the input values as well as to allow a professional quality printout of the cross section for reports.

Note on the figure the provision of the geometric properties including the gross and transformed moment of inertia (I), section modulus (S) and centroidal axis. The modular ratio, Es/Ec, used in calculating the transformed section properties is given as n. Note also the material property plots. Most of the values for these plots were selected automatically based on the input values. For example the concrete maximum aggregate size was assumed to be 10 mm, and the strain at peak stress as well as the tensile strength assumed. These values can all be changed by using the "Define | Material Properties" menu choice.

Analyses with Response-2000

With a column such as this, there are two possible failure modes, shear or flexure. Additionally, as the loading ratios are different in the push and pull direction, independent analyses will need to be done each way. Figure 7 shows the bending-moment diagram as well as the shear-force diagram for any value of the lateral load. As Response-2000 is a sectional analysis tool, the appropriate section to analyse must be chosen.

Figure 7: Shear Force Diagram, Bending Moment Diagram and Response-2000 Analysis Locations



For the flexural analysis, the location with the highest moment (section A in Fig. 7) is the location at which to do the analysis.

For the shear analysis, a failure would be accompanied by diagonal cracks similar to that drawn in Fig. 7. As it isn't geometrically possible for such a crack to exist completely at the extreme end of the column, it is appropriate to move away from the location of maximum moment a certain distance (Section B in Figure 7). A good value for this distance is dv, the flexural lever arm for the section. In this case, dv can be taken as three quarters of the total section depth. Another reason to do the analysis away from the end is that there will be substantial confinement at the end due to the presence of the large loading block at the top and bottom. For the section to fail in shear, it would have to expand transversely, but the loading blocks will restrain this expansion, forcing the shear failure away from the ends. The photograph in Fig. 5 provides clear evidence that the critical region for shear is some distance away from the end supports.

Shear Analysis with Response-2000

As the shear analysis is more interesting than the flexural, it will be done first. The pull direction loading ratios will be used. To do the analysis, the loading must first be defined. From Fig. 7, it can be seen that the moment at section B is (1.219 m - 0.75 x 0.610 m) x H (kNm) = 0.762 x H (kNm) where H is the horizontal load. The compressive axial load is 994 - 4.33 x H (kN). To enter these values into Response-2000, select the "Loads | Loads" dialog box and enter the following numbers in the 6 input boxes as shown and select "ok":

Constant Term Increment Term Comments

-994.0	4.33	(negative is compression for axial load)
0.0	0.762	(positive moment is compression on "top" of section)
0.0	1.00	

At this point, select "Solve | Full Response" to perform the analysis. All sorts of things should start happening now.

Interpreting the Results of Shear Analyses with Response-2000

This analysis takes a little while as it is considering shear by performing biaxial analyses at many points through the depth of the column. Additionally, it is finding the shear stress distribution by an iterative dual section analysis. The extent of the calculations can be seen by glancing through the 1978 paper appended to this report. In the 1988 paper, also appended, the method is described as being "too complex for regular use in the design of simple beams." Given the programs and the computers available at that time, this statement was appropriate. With Response-2000, the section can be entered in about a minute and with a modern Pentium machine, the analysis takes about 30 seconds.

The screen will be divided into a grey part at the left and a set of 9 graphs on the right. In the grey section, there will be 2 "control charts" forming at the bottom. They represent the sectional response (moment vs curvature and shear vs average shear strain) and will be updated as the analysis continues. After each load step, the 9 plots on the right will be updated too. They represent what's going on inside the column at the load level where the yellow cross hairs are on the control chart.

The nine plots shown are as follows (and printed in Fig. 8 for the 2nd last load step):

- **Cross Section** showing the depth of cracking and state of reinforcement (red = tensile yield)
- **Longitudinal Strain** Note the fundamental assumption of plane sections remaining plane. The units are parts per thousand, or mm/m.
- **Transverse Strain** is the strain (parts per thousand or mm/m) by which the column is getting deeper during the analysis.
- **Crack Diagram** shows crack pattern and widths in mm. Note that the shear results in diagonal cracks.
- **Shear Strain** distribution across the section. The strains vary substantially over the depth The jagged appearance is explained below
- **Shear stress.** This shows the distribution of shear as determined from the dual-section analysis (dual-section analysis is the method that Response-2000 uses to allow an analysis with shear to be done at a section using only the assumption of plane sections). There are 2 lines shown, a blue one and green one. The blue line is the calculated shear stress given the strain state, and the green line is what it should be given the results of the dual section analysis. If these don't match very well, the load stage should be treated with some caution.
- **Principal Compressive Stress.** This shows the distribution of compression over the depth of the section. Note that unlike the more familiar no-shear case, it is quite possible to have compression over the entire height of the section due to the shear forming diagonal compression struts in the "web" of the column. The red line at the left is the maximum allowed compressive stress. This maximum allowable stress reduces as the principal tensile strain increases. (as the cracks get wider, the concrete effectively gets weaker). If the two lines are touching anywhere, then the concrete is crushing and the section will fail.
- **Shear on the Crack.** The modified compression field theory, on which Response-2000 is based, calculates that on a crack surface, shear may exist in cases where the steel is yielding or where steel only exists in one direction. The calculated shear on the crack is shown in blue, and the

maximum allowable is shown in red. This maximum allowable is a function of the crack width at that depth and the aggregate size. If the shear on the crack reaches the maximum, the tensile stress in the concrete is reduced to ensure equilibrium is maintained. For members without transverse reinforcement, the maximum shear capacity of the section often occurs when these two lines touch.

- **Principal Tensile Stress.** Response-2000 considers that cracked reinforced concrete, on average, has a tensile capacity. This graph shows the current calculated stress (blue) and the maximum allowable value (red) determined on the basis of the longitudinal steel stress at a crack. When the longitudinal steel begins to yield at crack locations, the maximum allowable stress reduces.

On completion of the analysis, it is possible to click on the control chart to change the currently viewed load step. An alternative is to use the Page-Up and Page-Down key to go to the next higher or lower load stage. Try moving around to see how the graphs change while moving through the loads.

A number of things about the results are worth examining:

The shear stress and shear strain, vary greatly over the depth of the section. Recall from mechanics that the shear on the top and bottom surface of the section must be zero. This is true for all load steps. Recall also that for a rectangular beam, the elastic shear stress profile should be parabolic. Observing the first load stage, it can be seen that it isn't parabolic in this case due to the distribution of longitudinal reinforcement and the fact that it isn't a rectangular section, but that it is similar to a parabola with the maximum at the neutral axis. At higher loads, the cracking has a substantial impact on the shape and distribution of the shear stress and the shear strain.

After cracking, observe the jagged pattern of many of the graphs. This is a result of the discrete reinforcement in the concrete. As the shear flows down the section, parts are taken up by the individual longitudinal bars, causing the jumps. The analysis automatically considers how much shear is associated with each longitudinal bar, whatever the distribution of bars.

Note the redistribution of shear stress at the end of the analysis. At this load, the bottom longitudinal steel can be seen to be yielding (red on cross section plot at the top). Because of this, there isn't any ability to carry shear in that lower area as the longitudinal stress in the bars cannot change. The shear stress therefore moves higher in the section to where it can still be resisted.

Observe the cause of failure: local crushing of the web and high shear strains and high transverse strains just above the location where the lower hoop ends. That is, about 75 mm up from the mid-height of the section. In the second last load stage (as printed in Fig. 8), the maximum allowable compression is approaching the applied stress. At the last load stage, the hoops have ruptured (very high strain) and the concrete stress has disappeared in the crushed region. While there is longitudinal yielding, there is still plenty of flexural capacity in the non-yielding bars. This local crushing of the web is symptomatic of a longitudinal shear failure. It can be seen in Fig 5 that in the test, the concrete failed by crushing at about the same place as predicted by the analysis, over a substantial height of the column.

On the photo as well, note that the crack patterns near the region of analysis are reasonably accurate. The test was reverse cyclic, so there are cracks in both directions, whereas the analysis was monotonic and therefore, of course, only shows cracks in one direction. The failure shear from the analysis is predicted to be 361 kN.

Flexural Analyses with Response-2000

To check whether flexure governs the failure, an estimate of the flexural strength is needed. Enter the following loads into the input fields of the "Loads | Loads" menu choice:

Constant Term	Increment Term	Comments
-994.0	4.33	(negative is compression for axial load)
0.0	1.219	(positive moment is compression on "top" of section)
0.0	0.00	

As the shear terms are both set to zero, the computer will perform a flexural analysis. An additional consideration is that of the effect of the confinement due to the loading blocks. Just as this will tend to strengthen the column in shear (forcing any shear failure away from the end), it will also locally increase the moment capacity. It is well known that due to end restraint, concrete measured by a cube test is stronger than the same concrete tested as a standard cylinder. The Norwegian concrete code suggests that for this grade of concrete the strength of a standard cube is stronger than a standard cylinder by 25%. For this analysis, it will be assumed that the end confinement increases the concrete strength locally by 25 %.

To change the concrete strength, select the "Define | Material Properties" page and change the value for the concrete from 37.0 MPa to 46.3 MPa and click "ok" to exit.

Again select "Solve | Full Response". On a Pentium-200, this analysis takes about 2 seconds.

Interpreting the Results of Flexural Analyses with Response-2000

Once again the 9 plots are shown, but now they are a different set. The control plots are still there, but the top one is now the axial load vs centroidal longitudinal strain.

The following plots are shown (they are printed in Fig. 9 for the maximum load stage):

- **Cross Section** as before
- **Longitudinal Strain** as before. The units are parts per thousand (mm/m or milli-strains)
- **Shrinkage and Thermal Strains.** (as none were specified, it is blank.)
- **Crack Diagram** showing the crack widths in mm. As it's a pure flexure case, the cracks are vertical
- **Average Longitudinal Steel Stress.** Average stress considering both the steel at a crack and between the cracks (Units = MPa or ksi. Note that there is some strain hardening at the bottom)
- **Longitudinal Steel Stress at a Crack.** Note that the stress at a crack is higher than the average steel stress.
- **Longitudinal Concrete Stress:** The concrete is crushing at the top. (indeed from the longitudinal strain graph at the top, the strain is 3.28 mm/m)
- **Internal Forces:** resultants of the compression and tension forces of both concrete and steel
- **Stress Resultants:** Arrows show the sense of the moment and axial load

From this analysis, the maximum moment can be seen to be 502 kNm. This can be converted into an equivalent shear for the purposes of comparison. Consider from Fig. 7, that to obtain a moment of 502 kNm at the end of the column, the lateral load would need to be 502/1.219 = 412 kN. As such, the maximum possible lateral load for flexural failure is 412 kN. As this is greater than the 361 kN needed for a shear failure, the shear failure is predicted to control at 361 kN. In the test, the specimen did fail in shear at about 379 kN.

Producing Presentation Quality Figures with Response-2000

Response-2000 performs an enormous number of calculations and generates a very large amount of information. A considerable effort in the development of the program has gone into allowing the results to be easy to comprehend and to present. We believe that this program has the ability not only to predict the failure strength of reinforced concrete, but also to improve the users understanding of the behaviour of reinforced concrete. A necessary prerequisite to this is the ability to easily explore possible options, and then express them to others. As graphical presentation is perhaps the most efficient way to express a large amount of information, there are a number of tools incorporated to that end.

As an example, consider Figure 10 which shows the shear/shear strain plot for the UCSD Inter-4 Specimen with a series of small crack diagrams pasted on to show how the predicted crack widths and crack patterns change with load. Also drawn is the beam cross section and some text. This shows in a compact form the cross section, the sectional behaviour in shear, the predicted crack patterns, and predicted crack widths over the life of the column. For many purposes, this may represent enough information in one page to tell a full story about, say, how safe a column is with a given crack width. This figure was created with the "View | Load-Deformation Plot" which can also be selected by clicking on the little toolbar-button at the top of the screen that has a lambda on it.

The default graph can be changed with the top left selection box. For the last analysis it will show a moment-curvature diagram. After the shear analysis, it would have shown a shear/shear strain graph. To add in the beam cross section, select the "options | insert beam graphic" menu choice. Then by clicking and dragging it, it may be moved. By clicking on the corners of the plot and dragging, it may be resized as well. The same is true for the "options | insert text" menu choice.

Also on the left is the middle box called "paste data". From here the user may select a chart type, which is previewed (the default choice is longitudinal strain graph). After selecting the type, the user may change the currently viewed part of the curve with the control chart at the bottom and then click the "add to graph" button to add it onto the graph where it may be moved and resized.

All graphs in Response-2000 may be customized by right-clicking on the graph and choosing from the various choices.

Results from Push Direction

The results presented so far are for the case where the column was pulled towards the load actuator. For the push direction, there are few changes. Obviously the geometry is the same, only the loading needs to be changed. First change the concrete strength back to 37 MPa. For the shear analysis, enter the following loads in the "Loads | Loads" Dialog box and select "Solve | Full Response".

-944	-2.45
0	0.761
0	1.00

As the compressive axial load increases with lateral load this way, the shear strength is higher than before. Note that there is very substantial compression throughout the section depth of the section. Failure is predicted at a shear of 657 kN, by compression crushing in the web associated with very high transverse strains and shear strains occurring about 90 mm from the mid-depth.

For the flexural analysis, change the concrete strength to 46.3 MPa as before, and enter the following values in the "Loads | Loads" dialog box:

-944	-2.45
0	1.219
0	0.0

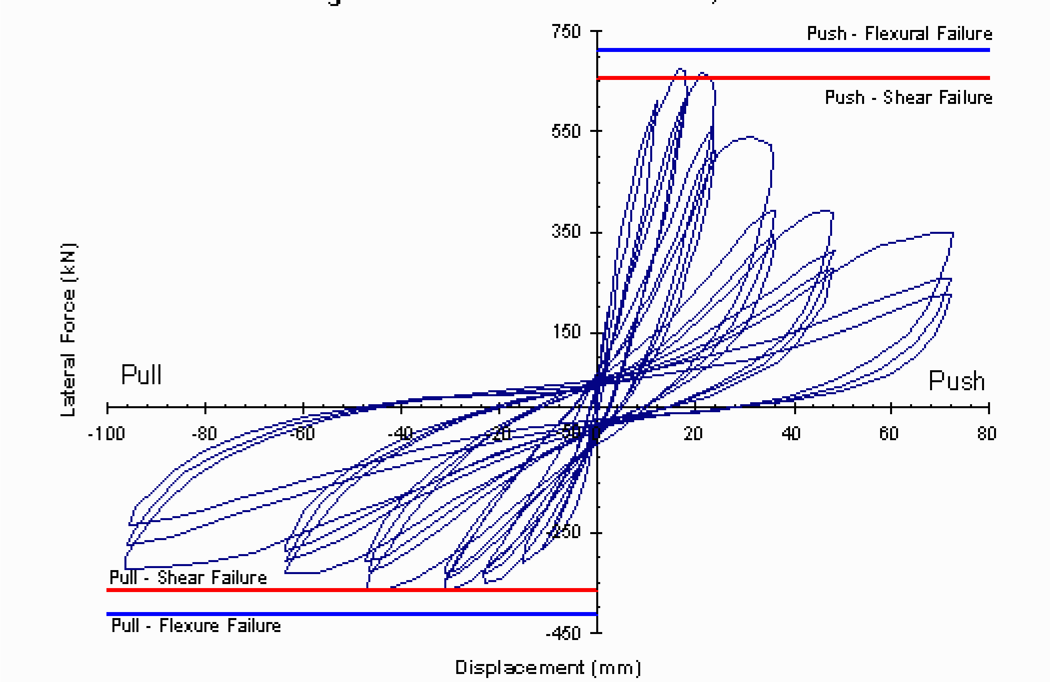
In this case, the maximum moment is 866 kNm. This corresponds to 866/1.219 = 710 kN of lateral load.

As such, failure is predicted to be in shear at a lateral load of 656 kN. In the test, the failure was in shear at a load of about 677 kN.

Predicted Strengths

Figure 11 shows the predicted strengths drawn on top of the hysteresis loops from the test. In both directions, the shear and flexure results are shown. Obviously the one with the lower absolute value would control the failure. Clearly the predicted strength and mode of failure in both directions are predicted well by Response-2000.

Figure 11: Load-Deflection Inter-4, UCSD



Predicting Load-Deflection with Response-2000

As Response-2000 calculates the full load-deformation state for a concrete cross section, a number of sections can be assembled "back to back" and then the deformations can be integrated to estimate the load-deflection history of the member. This form of pushover analysis can be quite useful for a number of applications.

Figure 12 shows the method used to integrate the stresses for Inter-4. Response-2000 doesn't do this automatically yet, so it was done with another specially written program. Using a smaller number of sections (say 5), results could be obtained by hand reasonably quickly with acceptable accuracy.

Figure 12: Method of Calculating Load-Deformation Curves With Response-2000

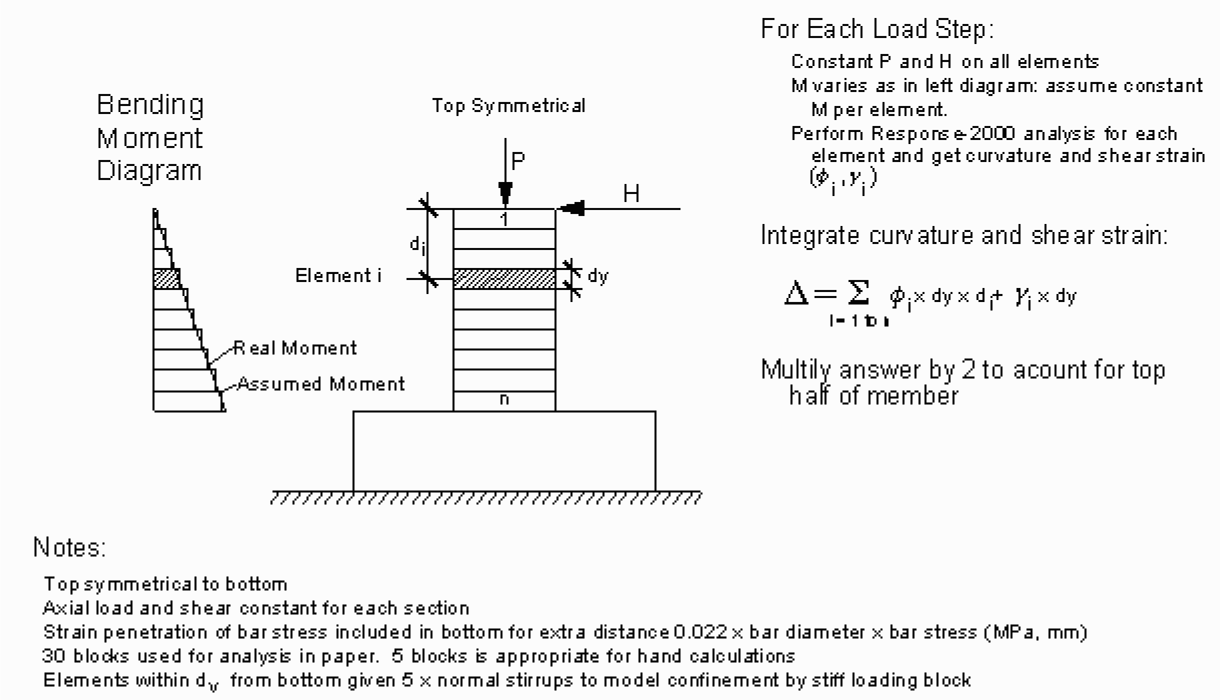
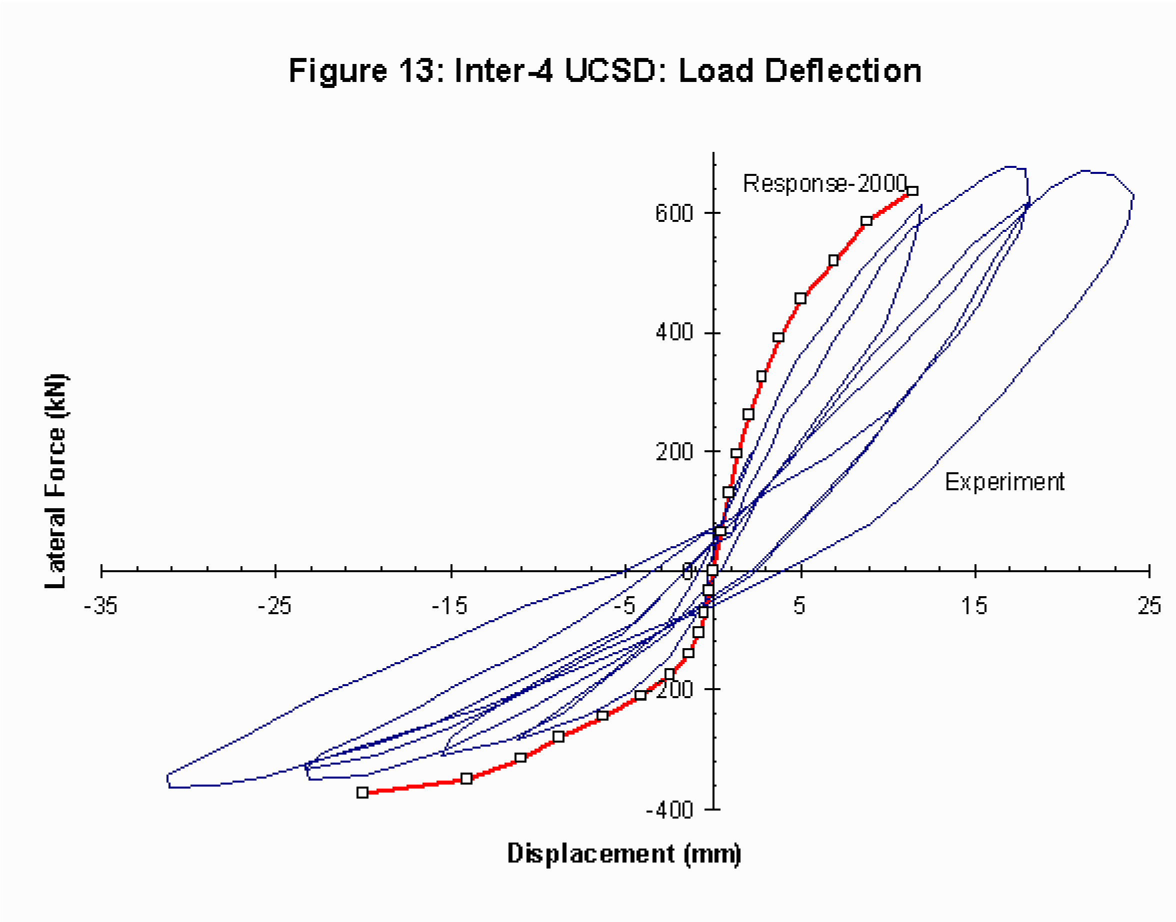


Figure 13 shows the results of this analysis. The results can be seen to be quite good. They aren't as good in the push direction as in the pull with the test being somewhat more flexible than predicted. This would presumably result from fact that Response-2000 is calculating a monotonic response, whereas the test involves reverse cyclic loading. In the push direction, the calculations for monotonic response indicate that most of the specimen is uncracked for most of the load history. In the test, the specimen was cracked because of loading in the reverse direction.



Further Experimental Verification

To further demonstrate the capabilities of Response-2000, we will consider beam CF1 which was a prestressed concrete box girder with one simple support and one continuous support. (Prestressed Concrete Structures on pages 352-359) Note that box sections may be entered into Response-2000 as I sections. Figure 14 shows the predicted and experimental moment-curvature at a location below the point load applied in the middle of the span. The experimental curvature was determined from the measured longitudinal strains of the top and bottom steel. The analysis with Response-2000 was done without shear (i.e. a flexural analysis). The results obtained are remarkably good. Unfortunately, this level of precision is unusual!

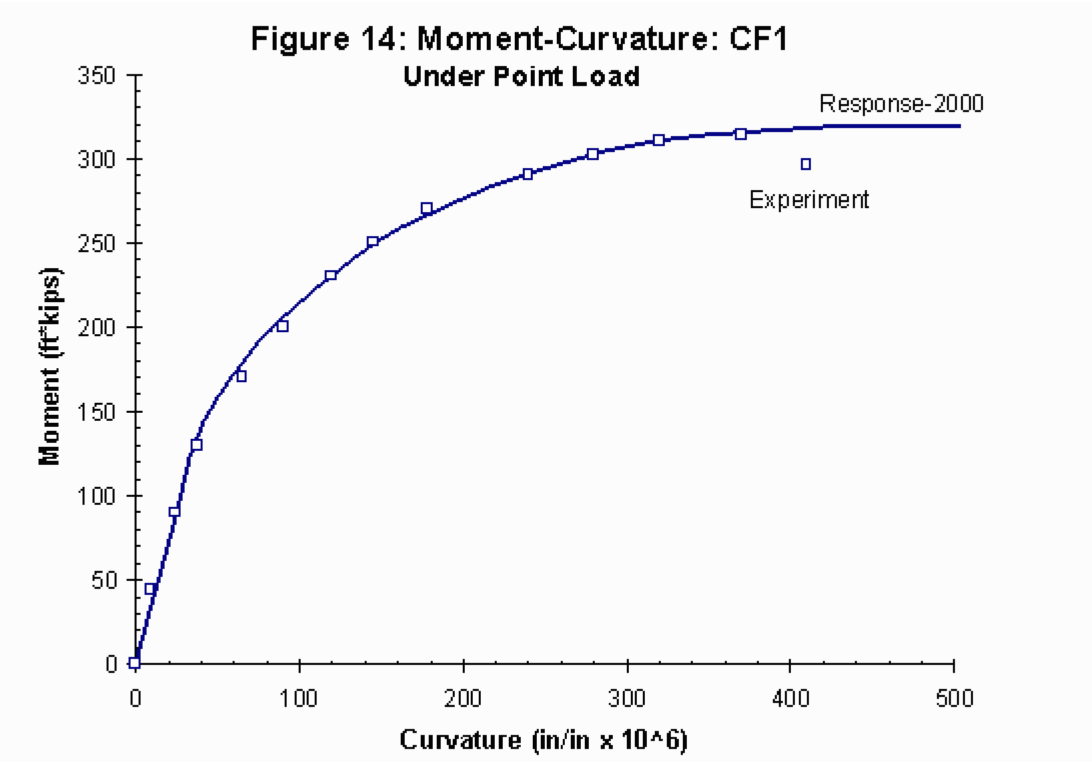
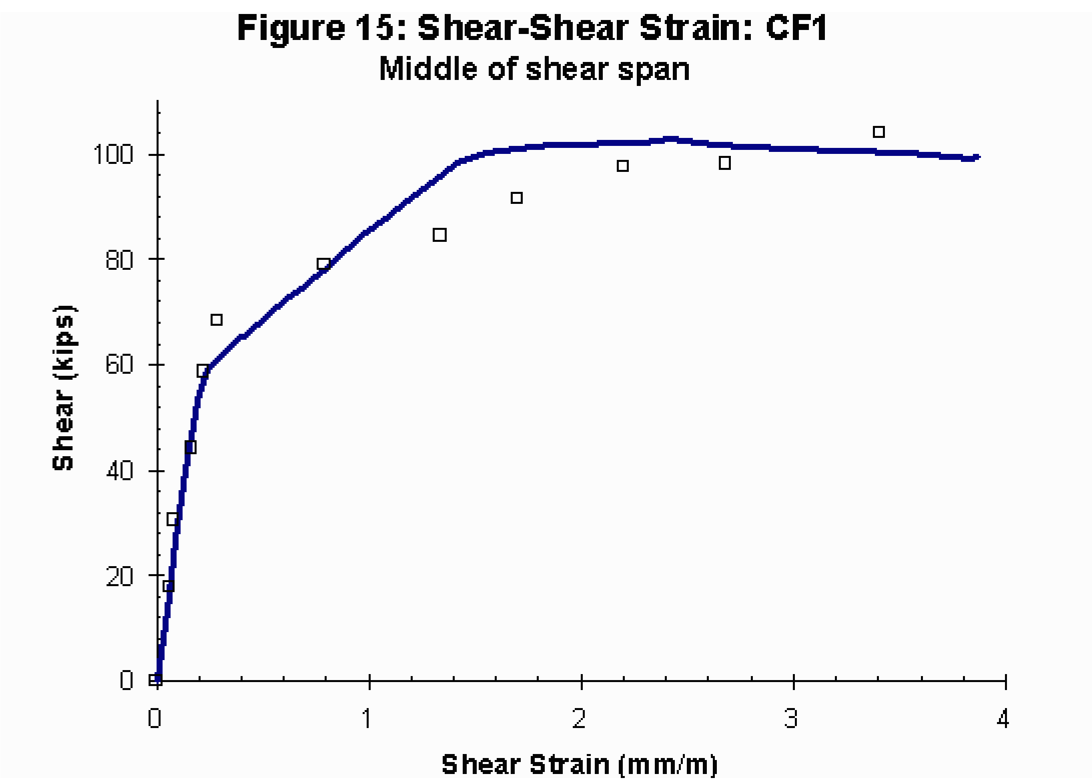


Figure 15 shows the shear vs shear strain for the CF1 at a location halfway between the point load and the continuous support where the moment was equal to zero. The shear strain was measured by taking the difference in strain of two diagonals at 45 degrees to the horizontal. This agreement between predicted and observed failure shown in this figure is more representative of what can be expected for Response-2000.



For some purposes, the most important parameter from the analysis is the sectional strength. The following plots show some examples of the ability of Response-2000 to predict strengths for a variety of sections.

Figure 16 shows the results of 4 circular columns tested by Khalifa (Publication 81-08, Department of Civil Engineering, University of Toronto, 1981.) The main parameter in these tests was the amount of transverse reinforcement which varied from zero to 2.29 MPa. Additionally, these tests had an axial compression of about 30% of fc'. It can be seen that the predictions are excellent.

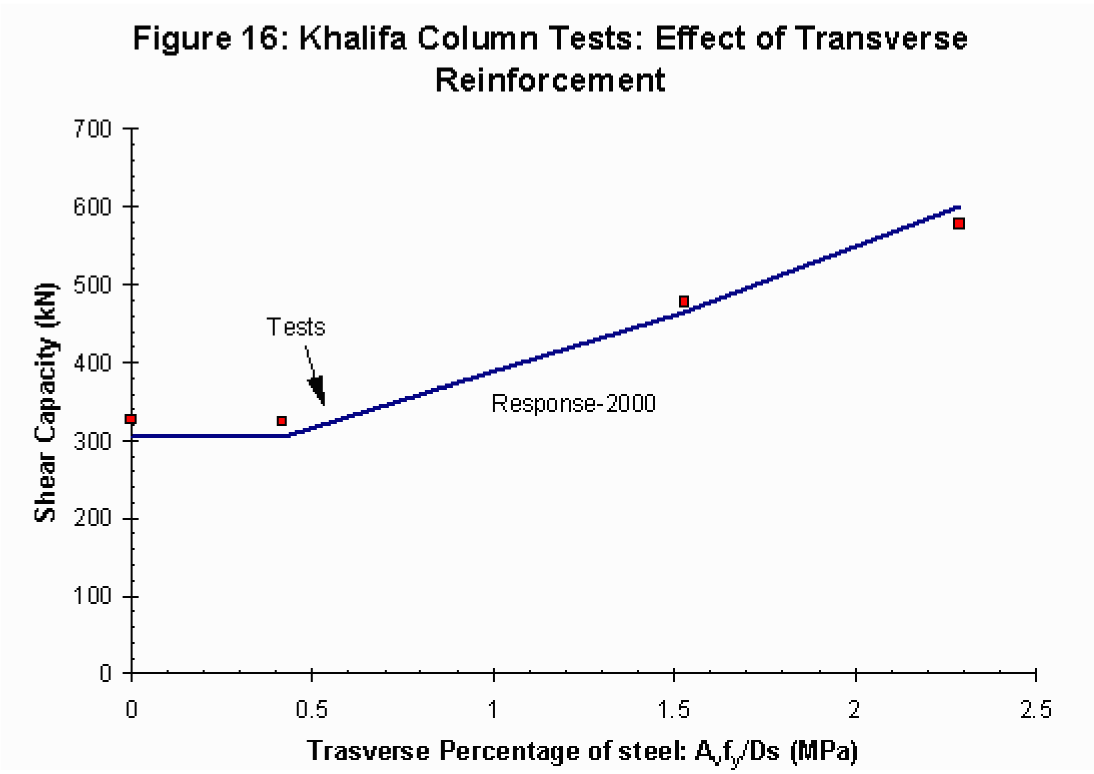
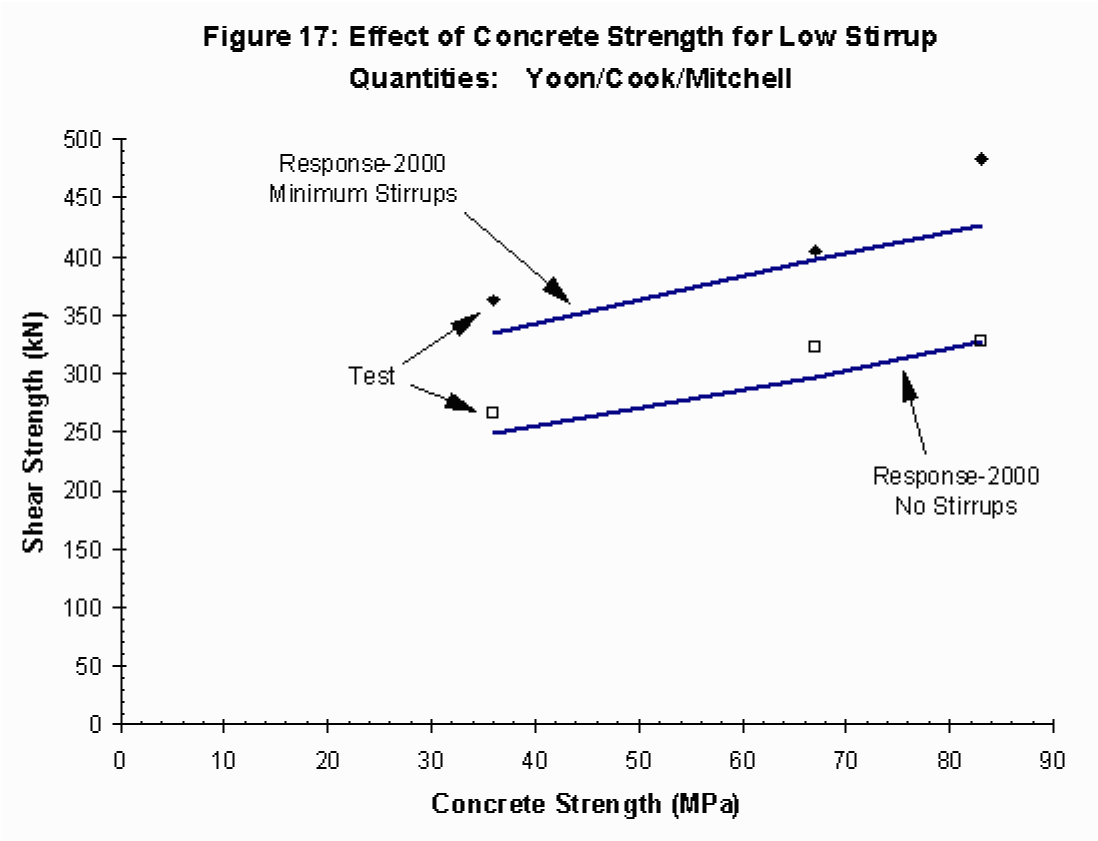
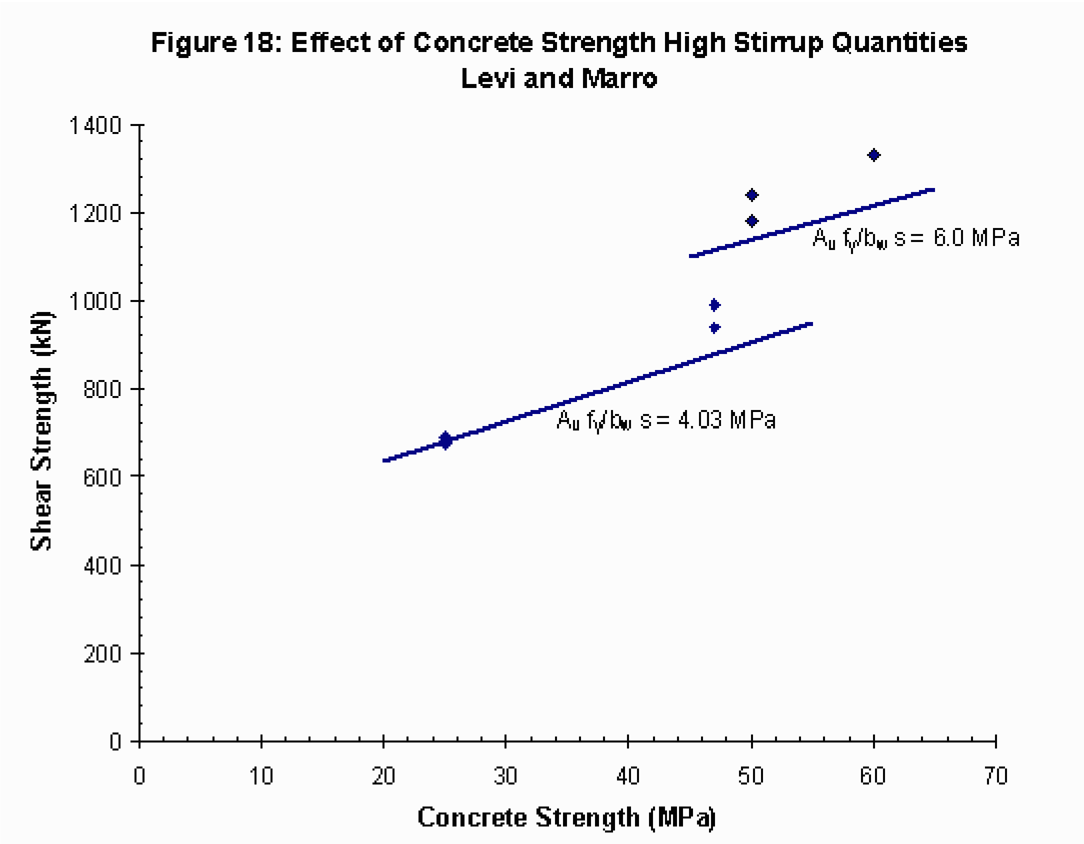


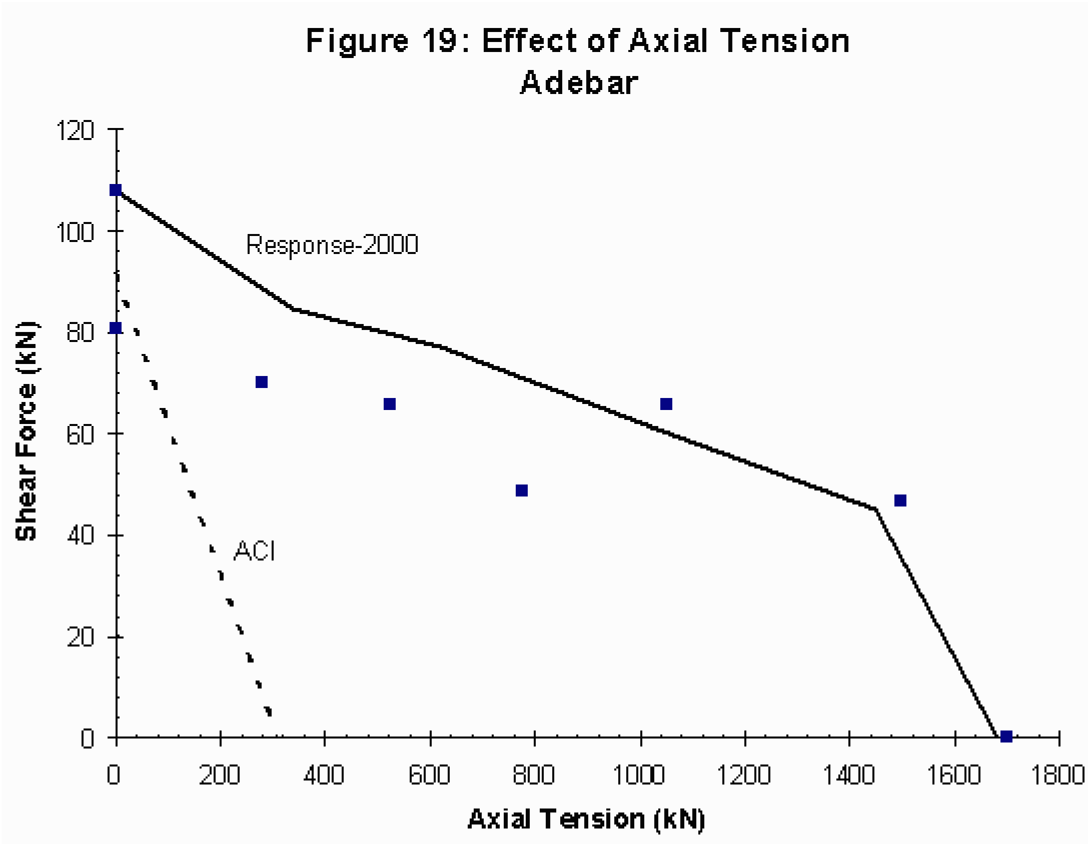
Figure 17 shows the results of tests carried out by Yoon, Cook and Mitchell as reported in the ACI Structures Journal, November December 1996. The tests were to examine the minimum reinforcement provisions of the code at different concrete strengths. The graph compares the predicted and observed shear strengths for cases with minimum and no stirrups. Note that the influence of concrete strength and amount of stirrups are both very well predicted.



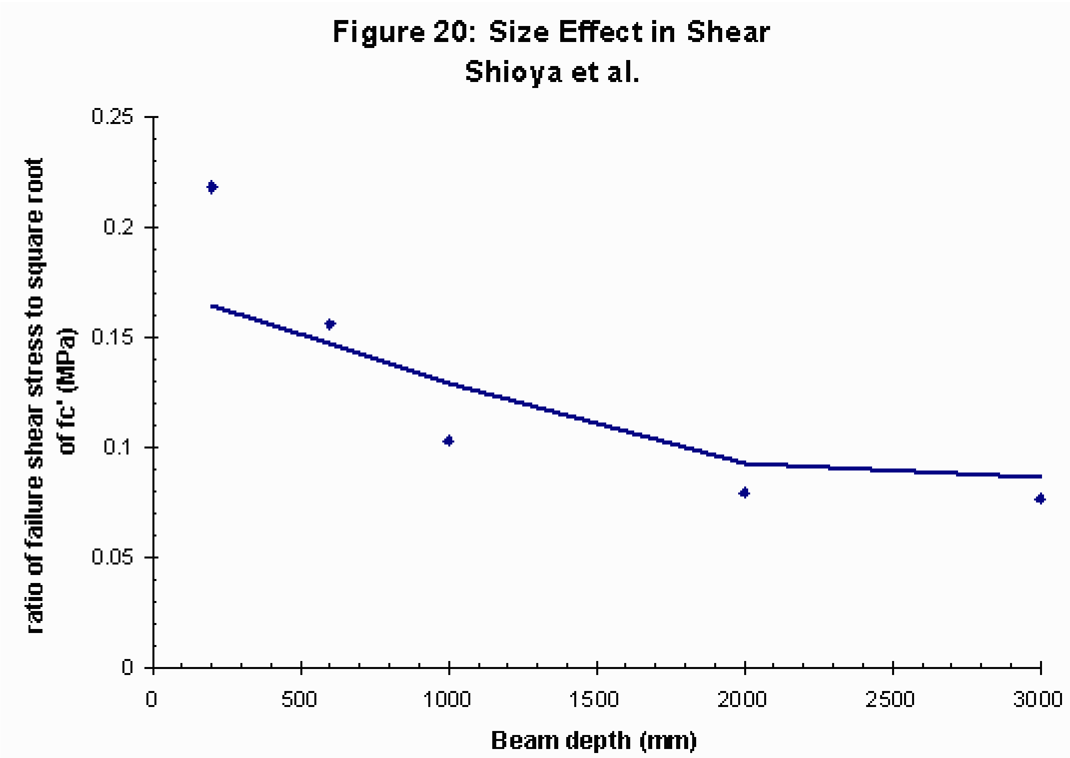
While Yoon Cook and Mitchell tested members with very small amounts of stirrups, Levi and Marro tested I beams with very large amounts of stirrups, (CEB Bulletin No. 193, December 1989.) These beams failed by web crushing and it is interesting to observe how accurately Response-2000 predicts this type of failure. Again the influence of concrete strength and amount of stirrups are both accounted for very well.



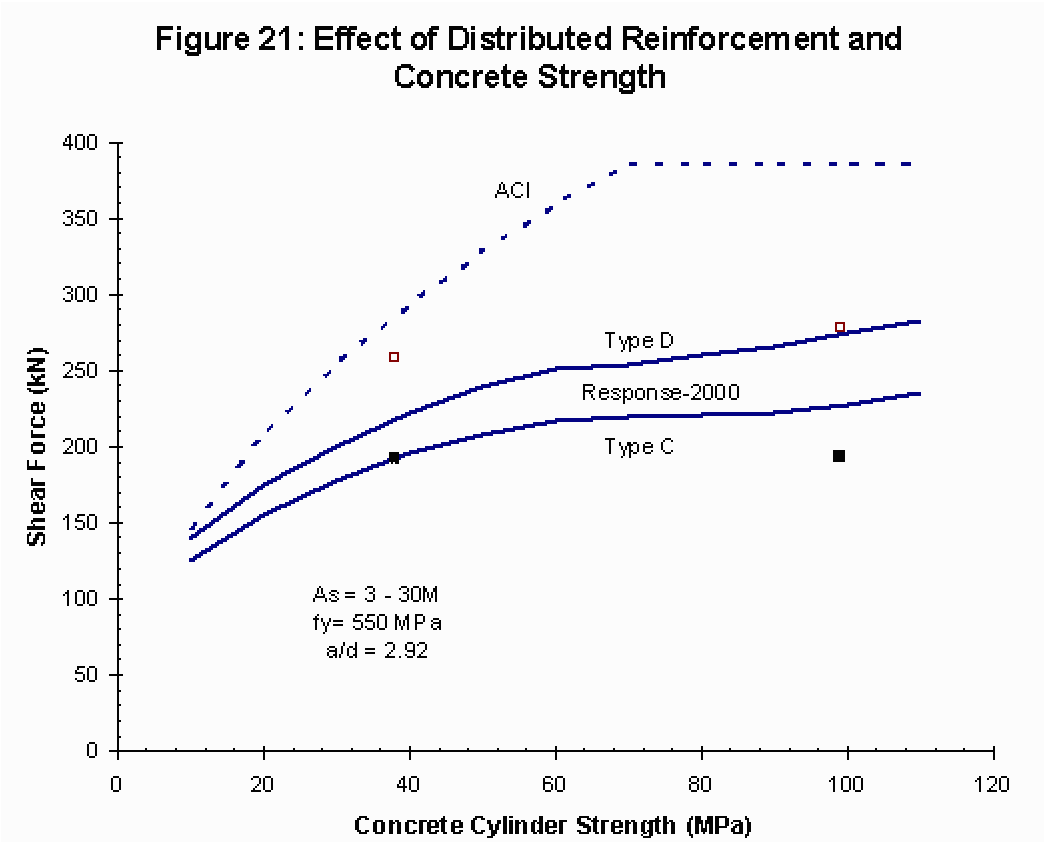
For members without stirrups, the ACI code suggests that the shear strength is very sensitive to axial tension, reducing to zero for an axial tensile stress of 500 psi. Figure 19 compares the ACI and Response-2000 predictions with experimental results reported by Adebar and Collins, Canadian Journal of Civil Engineering, January 1996. It can be seen that the ACI predictions are very conservative for the members with high tensions



The ACI code assumes that members without stirrups can resist a shear stress of 2 x sqrt(fcp) (psi units) prior to failure. This value was based upon laboratory tests which primarily used beams about 300 mm deep. Many recent tests have shown that the failure shear stress reduces as the member size increases. Figure 20 compares the effect of size on failure shear stress observed by Shioya et al, (ACI SP118, 1989) with the predictions of Response-2000. Note that in MPa units, the ACI value is 0.167 which is very unconservative for the deep beams.



In the modified compression field theory, the shear capacity of a member without stirrups is related to the width of the diagonal cracks. These crack widths are in turn related to crack spacings. Larger members have larger crack spacings and hence fail at lower shear stresses. In Response-2000, a modified version of the 1978 CEB expression is used to calculate crack spacings. For a particular location in the section, the crack spacings are assumed to depend on the distance to the nearest reinforcement, the diameter of this reinforcement, and the percentage of reinforcement. Members with distributed longitudinal steel are predicted to have smaller crack spacings and hence higher shear capacities. Figure 21 shows the shear failure loads for 4 large beams, 2 of which had distributed steel. It can be seen that for these two pairs of beams, adding distributed steel increased the shear capacities by about 40 %. (Kuchma et al CEB Bulletin 238, April 1997)



Crack widths increase not only as crack spacings increase, but also as strains increase. If a member contains smaller amounts of longitudinal reinforcement then for the same load, the strains will be higher. As a consequence of this, members with smaller amounts of longitudinal reinforcement will fail at lower shear forces. Figure 22 shows the results of 3 large beams recently tested by Dino Angelakos at the University of Toronto. It can be seen that as the percentage of reinforcement increased from 0.5 % to 2.0 %, the shear strength increased from 158 kN to 260 kN. The Response-2000 predictions closely follow the experimental trend. The simple shear strength expression in the ACI code would suggest that all 3 of these beams should fail at a shear force of 253 kN.

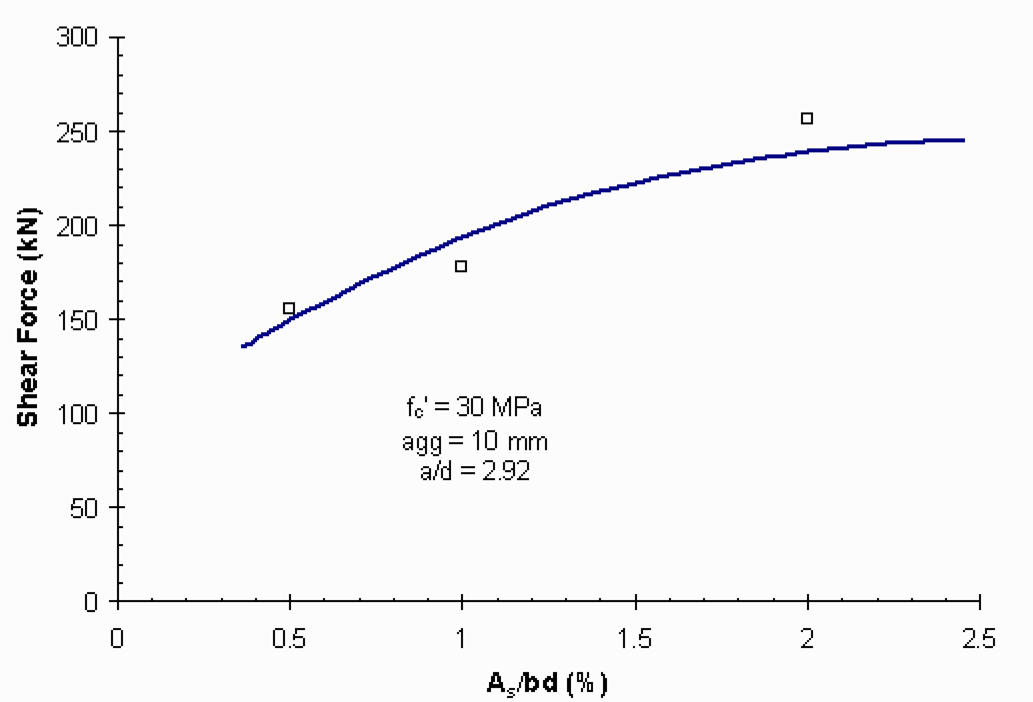
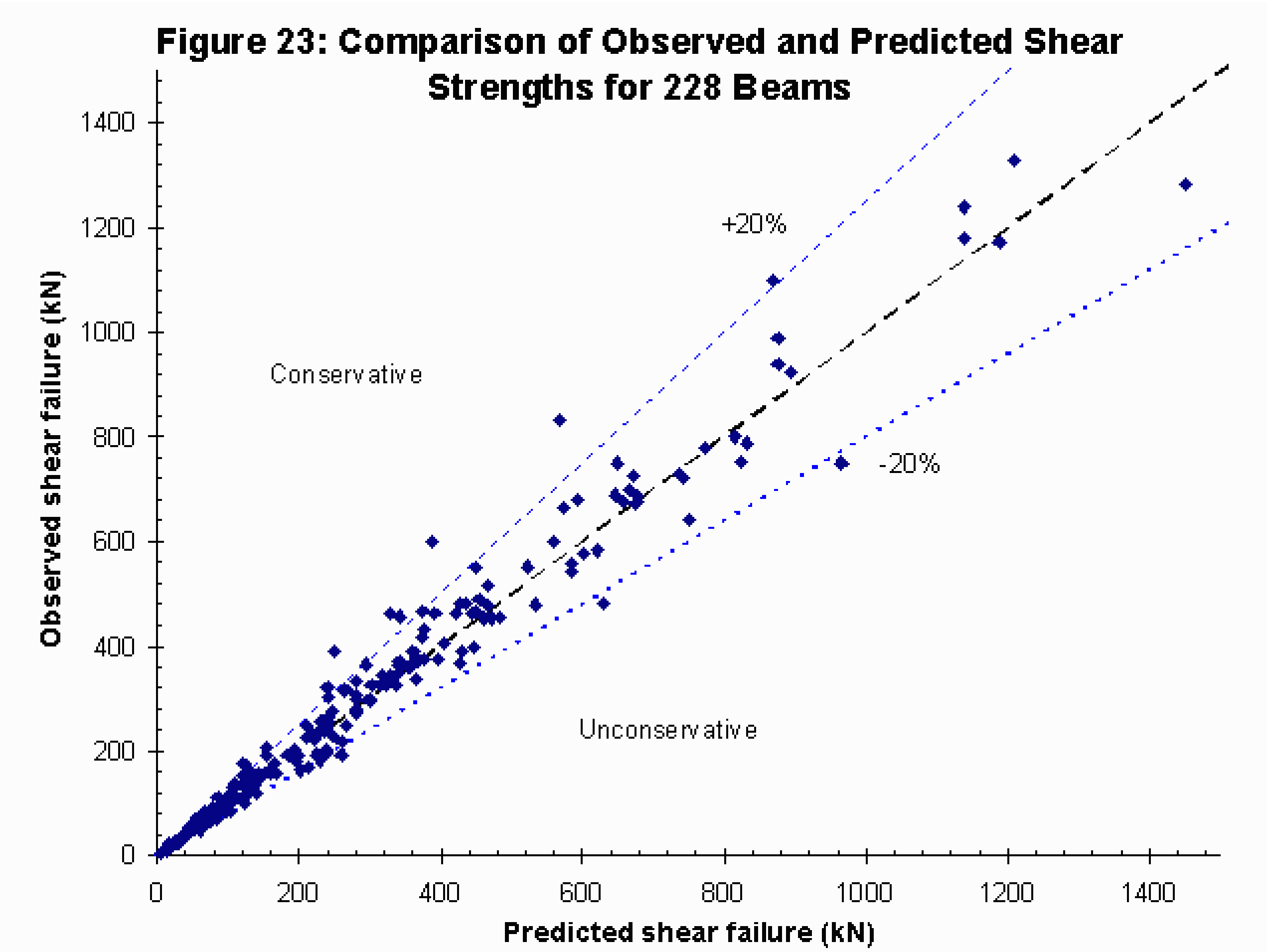


Figure 22: Effect of Amount of Longitudinal Reinforcement

While a more extensive experimental verification of Response-2000 has yet to be completed, 228 tests have been entered into the program so far and compared to the experimental shear strengths. Of the 228 tests, 9 were circular sections, 26 were I sections, 15 were T beams, 3 AASHTO type sections, Inter-4, and 173 were rectangular. There were 97 tests of beams with stirrups, and 131 tests without stirrups. The average ratio of experimental shear strength to predicted shear strength for all the beams is 1.03, with a coefficient of variation of 11.9%. These results are shown in Fig. 23. The failure of members without stirrups is sensitive to the tensile strength of concrete. The assumed cracking strength used in the modified compression field theory is 0.33 x sqrt(fc') (MPa) or 4 x sqrt(fc') (psi) This value was found to be appropriate for members where shrinkage strains had already occurred. Specimens tested damp or very young display a higher tensile strength of about 0.42 x sqrt(fc') (MPa), 5 x sqrt(fc') (psi) See Vecchio and Collins, Publication 82-03, March 1982. Hence in predicting the shear strength of such specimens, it is appropriate to increase the predicted tensile strength by 25 %.



Program Availability

The beta version (0.7.5) of Program Response-2000 is being made available in the hope that people will provide us with feedback as to possible improvements to the program which we could consider for incorporation in the version 1.0 of the program. Full documentation of the program will be provided in the PhD thesis of Evan Bentz in 1999. The beta version is now available on the world wide web at the following address:

http://www.ecf.utoronto.ca/~bentz/r2k.htm

While considerable care has been taken in formulating the beta version of Response-2000, please be aware that it is a very new program and very probably still contains some dreaded bugs. Hence, particular care should be exercised in applying the results of Response-2000 to real engineering problems. Of course, the authors of the program shall not be liable for any damages arising out of the use of this program.