

**Parametric Flexural Evaluation of Concrete Members
Reinforced with High-Strength Steel**

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ABSTRACT

In the field of structural engineering, the usage of reinforcing materials must follow ASTM design specifications. The current AASHTO specifications for the usage of steel reinforcement only allow for strengths of up to 75 ksi. This research project aims to determine whether currently used models are sufficient for estimating moment capacities of beams reinforced with A706, N32, SS2205, A316, and A1035 steel rebars. With this information, we will be able to conclude whether or not revisions to the design codes are needed to implement the high-strength steel that is now available. Estimations of moment capacity computed using experimental data collected at the University of Cincinnati by master's student Elizabeth Ward and at the University of Pittsburgh by Dr. Kent Harries have been used to compare the elastic-perfectly plastic model, the Ramberg-Osgood model, and the XTRACT model. The expectation of these comparisons is to confirm that the current design codes and the models on which they are based are adequate for the implementation of high-strength steel in the industry. The report we will be publishing will be disseminated through presentations at our respective institutions.

Key Words: XTRACT, specifications, stainless steel, flexure, REU, NSF

1. INTRODUCTION

The research presented in this paper is a small part of an overarching project, NCHRP 12-77. Currently, the American Association of State Highway and Transportation Officials (AASHTO) design specifications for steel reinforcement in concrete cap design strengths of reinforcement in load-bearing members at 75 ksi. The goal of the NCHRP study is to better understand the behavior of high strength concrete and steel by testing reinforced members composed of 10-15 ksi concrete and A1035 steel to shear and flexural failure.

In order to allow the full application of these materials, it is necessary to determine if and to what extent current design specifications must be modified to adapt them to high strength steel and concrete. Because these specifications rely on assumptions about the behavior of the relevant materials, attention must be given to the applicability of current methods of estimating moment capacity to situations involving these materials. It is this applicability that is the focus of this paper.

2. BACKGROUND INFORMATION

One of the more important aspects of any structure is the materials from which it is built and their properties. One of the most commonly used materials in large structures is steel-reinforced concrete. Concrete has a high compressive strength but a very low tensile strength, so in order to make it suitable for many structural applications, reinforcement is needed to increase its tensile strength. This is typically done by adding steel reinforcing bars parallel to

its length to prevent flexural failure, and steel stirrups that lie parallel to the cross-section of the beam to prevent shear failure.

The material usually used as reinforcement in concrete is Grade 60 A615 steel rebar. However, newly available high-strength materials could be safer and more cost-effective than the current industry standard. Higher strength steel such as A1035 offers not only an increase in strength but also corrosion resistance. (Dwairi et al. 2004).

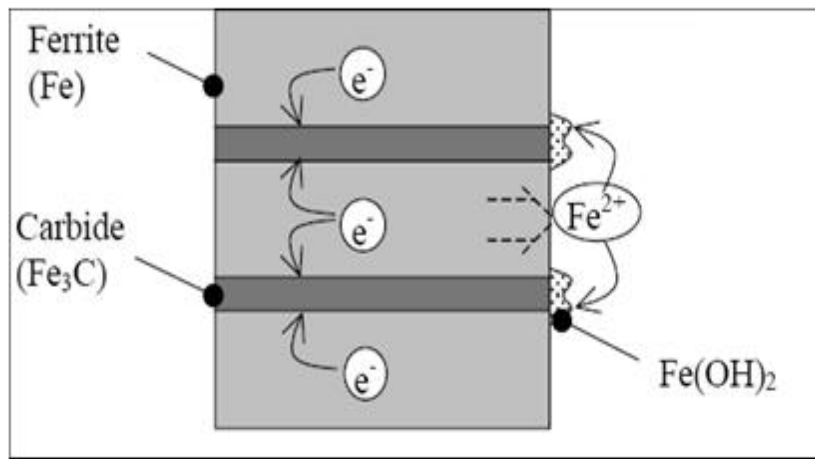


Fig. 2-1: Typical Steel Microstructure

The foremost impetus for adopting A1035 steel is perhaps its resistance to corrosion. This property is a result of its microstructure. A615 contains alternating bands of ferrite (Fe) and carbide (Fe₃C), thus creating a microgalvanic cell (Dwairi et al. 2004). The electrons from the ferrite travel to the carbide and this reaction creates corrosion byproducts. A1035 contains little carbide (almost none), resulting in a retarding of this reaction. This dramatically increases the service life of steel. In corrosive environments, A1035 has a service life of about 75 years, while A615 is expected to last only 15-30 years (El-Hacha et al. 2002). This difference can mean millions of dollars saved on repairs and rebuilds annually.

While a comparison study between the flexural performance and behavior in tension of A1035 and A615 steel has been done by Florida DOT, some questions remain unanswered. In FDOT's tests, A1035 proved, as one might expect, to exhibit greater strength and lesser ductility than the A615 specimens. The authors conclude, though, that although the A1035 steel performs favorably to the A615 steel, high-strength steel cannot simply be substituted for A615 due to its lesser ductility. It is suggested that the development of new design specifications for the configuration of reinforcement within beams will likely be necessary.

For mild steels, yield strength can often be determined by the location of a yield plateau in its stress-strain curve, where a yield plateau is a region of approximately constant stress connecting the elastic and plastic regions of the curve. Since high-strength steel often lacks such a defined yield plateau, accurate determination of yield strength is problematic. For this reason, FDOT's study calls for additional research aiming to accurately define yield strength for A1035 steel.



Fig. 2-2: Stress-Strain curve with apparent yield plateau

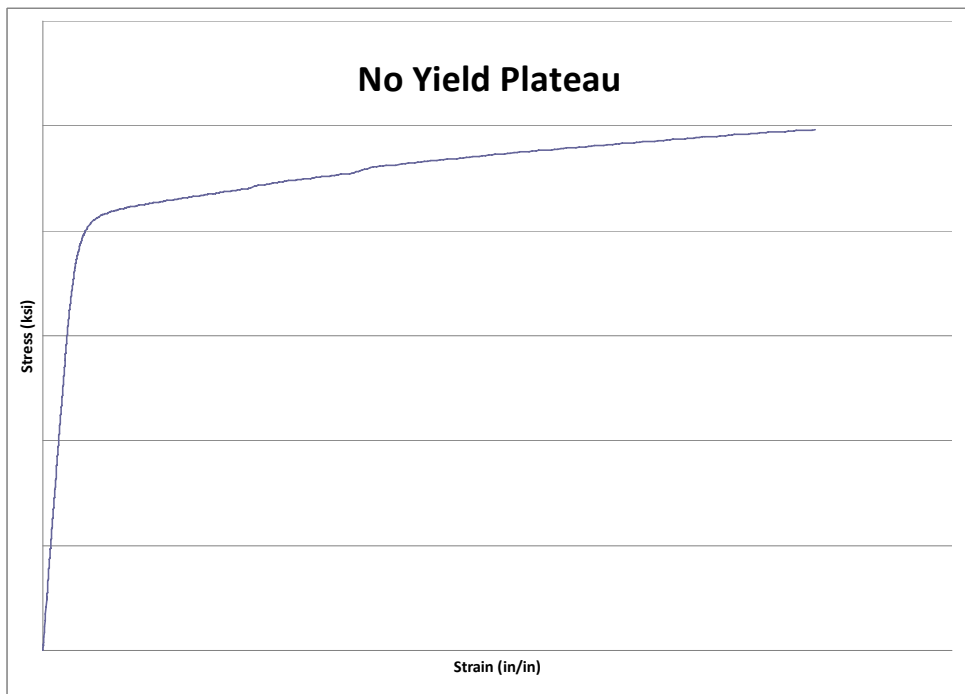


Fig. 2-3: Stress-Strain curve with no apparent yield plateau

3. GOALS AND OBJECTIVES

The objective of this project is to determine the applicability of commonly used methods of estimating the moment capacity of beams reinforced with mild steel to those reinforced with high-strength steel. Elastic-perfectly plastic (E-PP), Ramberg-Osgood (R-O), and fiber analysis models will be assessed for relevancy to high-strength reinforcement and revision to these standard methods may be recommended. Upon completion of our research we will present our findings to a panel for evaluation.

4. RESEARCH STUDY DETAILS

Essential to the success of NCHRP 12-77 is the use of mathematical models to find a good description of stress vs. strain in high-strength steel, and in particular, a good description of smooth elastic-plastic transition regions in order to make accurate estimations of moment capacity. The commonly-used methods of determining moment capacity will then be compared to this more accurate method. For this purpose, consideration will be given to several models of yielding behavior and methods of estimating moment capacity.

The first and the simplest determinations of yield strength come through the use of .2% and .5% offset methods. The yield strength estimated using this method will be used in conjunction with a moment capacity calculator. (Shahrooz, 2008)

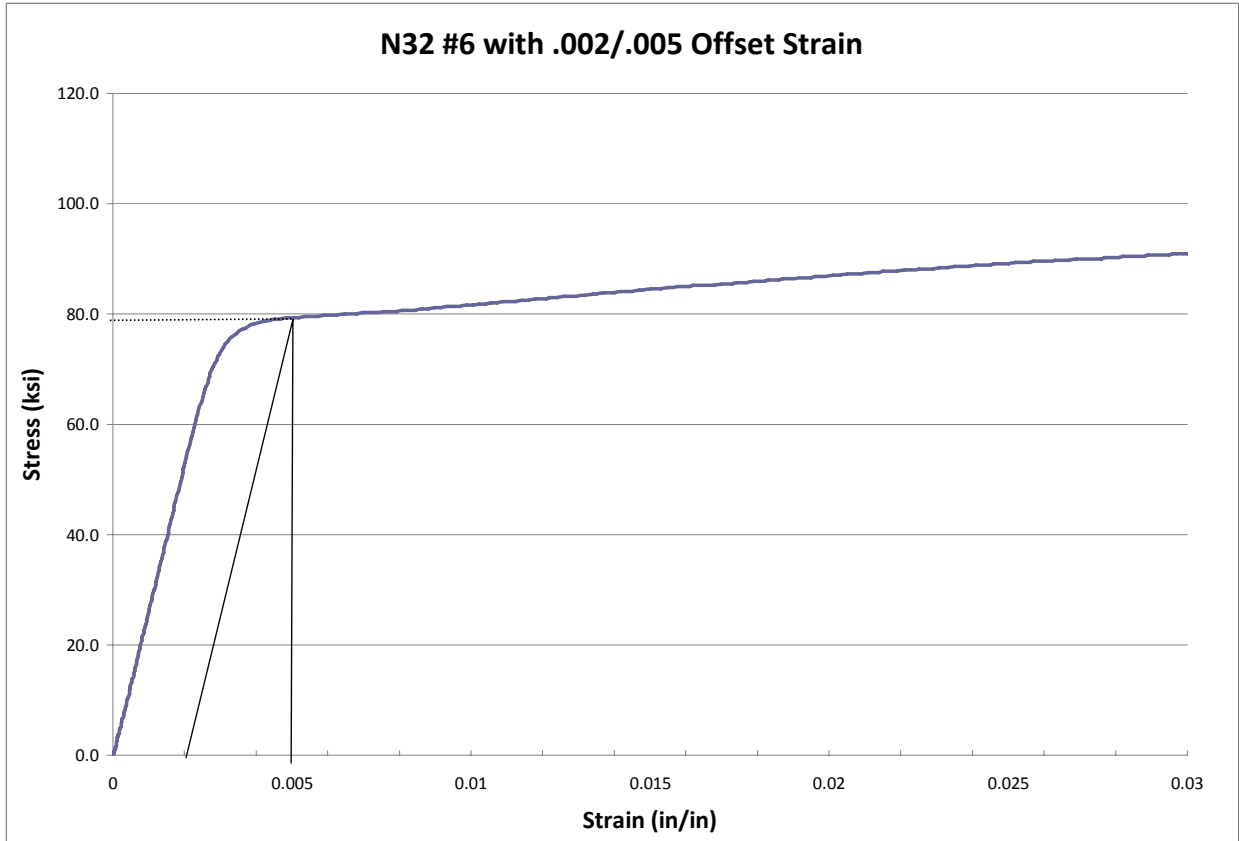


Fig. 4-1: .2% and .5% offset methods

The second, more descriptive model is Ramberg-Osgood:

$$f_s = E_s \varepsilon_s \left\{ A + \frac{1 - A}{[1 + (B \varepsilon_s)^c]^{1/c}} \right\} \leq f_s \quad (1)$$

Where

f_s = stress

E_s = steel's elastic modulus

ε_s = strain

A, B, C = R-O parameters

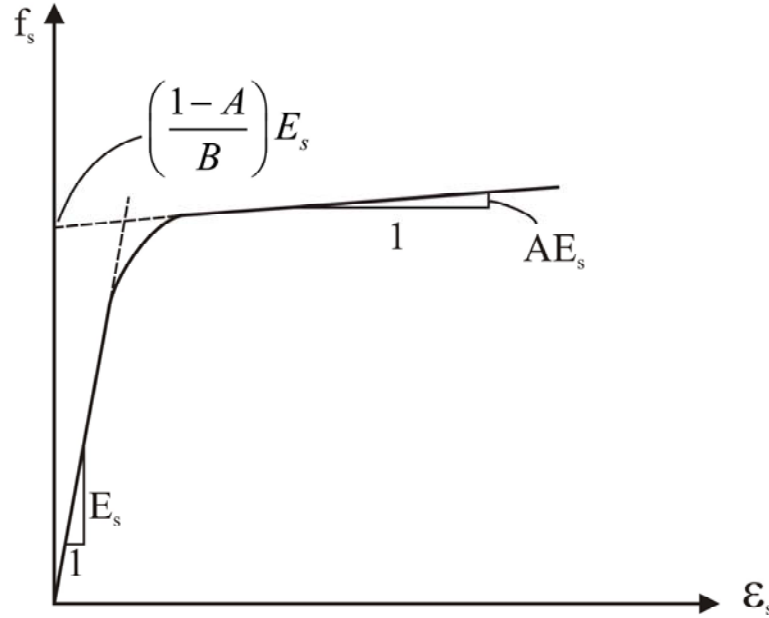


Fig. 4-2: R-O Slopes

This model begins by defining two secant lines, one describing behavior in the elastic region (where the slope is E_s) and the other describing behavior in the plastic region (where the slope is equal to the product of E_s and some constant, A). The smooth elastic-plastic transition is modeled by gradually changing the slope from E to EA as ϵ increases. This approach to modeling the smooth transition has been moderately successful in similar applications. Again, this data will be exported to and analyzed by Dr. Shahrooz's moment capacity calculator.

The third and most complex and accurate method of estimating moment capacity to be used is the XTRACT fiber-based cross-sectional analysis software. This software allows you

to draw a beam's cross sectional schematic, define the properties of the materials used by importing raw stress-strain data, and estimate moment capacity through iterative calculations.

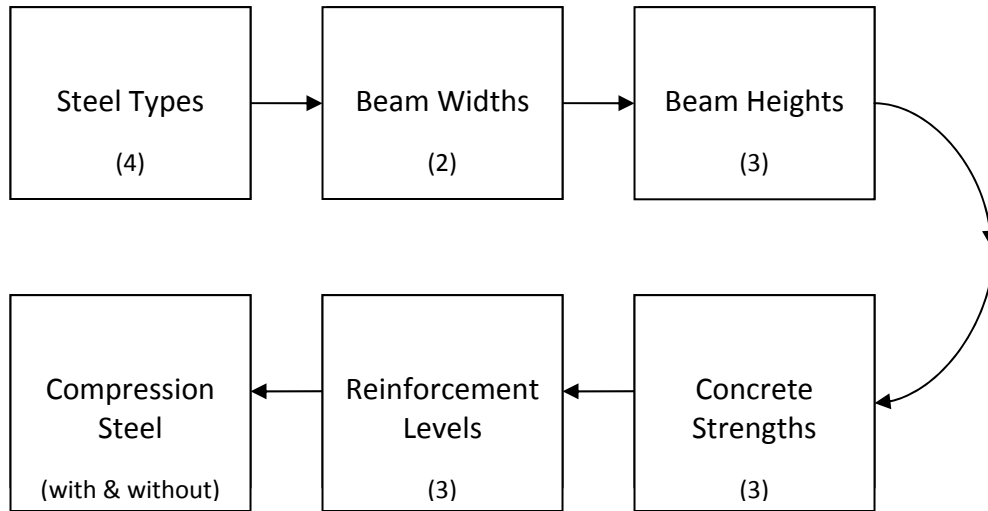


Fig. 4-3: Parametric Hierarchy

The permutational tree for cross sectional schematics used for this project, beginning at the ‘trunk’, is as such: four types of steel (A316, A706, N32, N2205), two beam widths (12 inch, 16 inch), three beam heights(16, 28, and 36 inches for 12 inch width, and 28, 36, and 40 inches for 16 inch width), three concrete strengths (5, 10, and 15 ksi), three configurations of tension steel(AASHTO minimum, maximum based on minimum steel strain of 0.004, and an average of these two values), and each of the previous cases with and without compression steel. This amounts to 432 permutations. This set of parameters was chosen to be similar in dimension to beams used in the field, and to cover a wide range of reinforcement.

5. ANALYSIS RESEARCH RESULTS

After uploading raw stress-strain data into excel, the data was corrected and plotted. The offset methods, as they entail only drawing lines and reading values, were applied to the data without issue. R-O curves were fit to each steel type with r^2 values above .95, and particular interest was taken to fitting it to the elastic-plastic region. The values retrieved here were then used in conjunction with the aforementioned moment capacity calculator and the output was compiled by steel type → beam width.

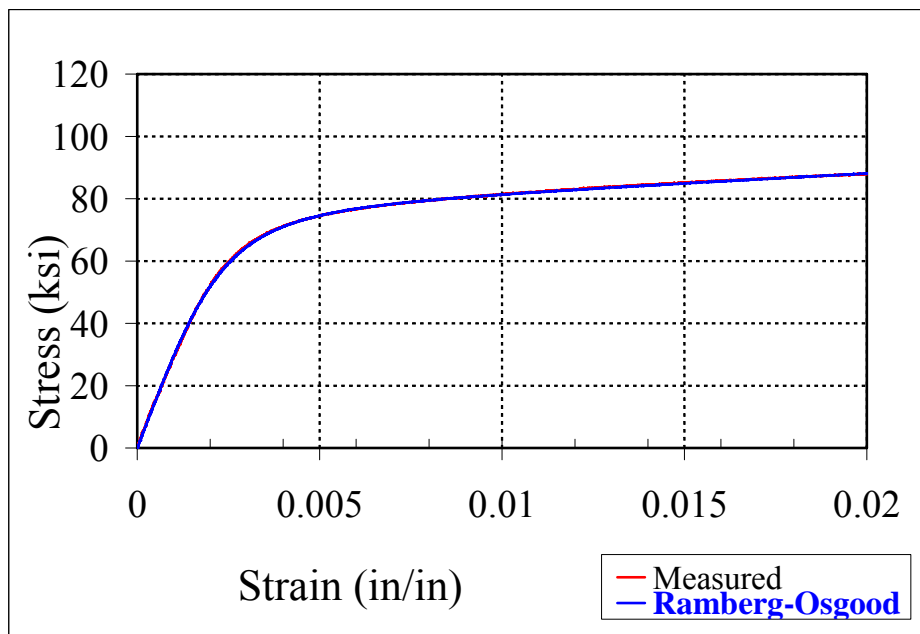


Fig. 5-1: Ramberg-Osgood Fit Example

The Steel data sets to which the offset methods and R-O were fit were reduced and imported to XTRACT.

Our analysis hinges on the assumption that the XTRACT estimates of moment capacity are closer to the actual value than any of the other methods. Data from each model was collected and compiled at the hierarchal level of steel type → beam width → beam height. For each case, a percent difference between the E-PP and R-O model vs. XTRACT has been calculated, and the moment-curvature graph was combined in a graph with lines depicting the capacities predicted using the E-PP and R-O models. In general, XTRACT’s estimation is greater than that of R-O or E-PP, and within 20% of their values. The only other general trend that is apparent at the extent of analysis that was conducted is that there is a greater disparity between the estimated values in cases that include the minimum amount of steel reinforcement

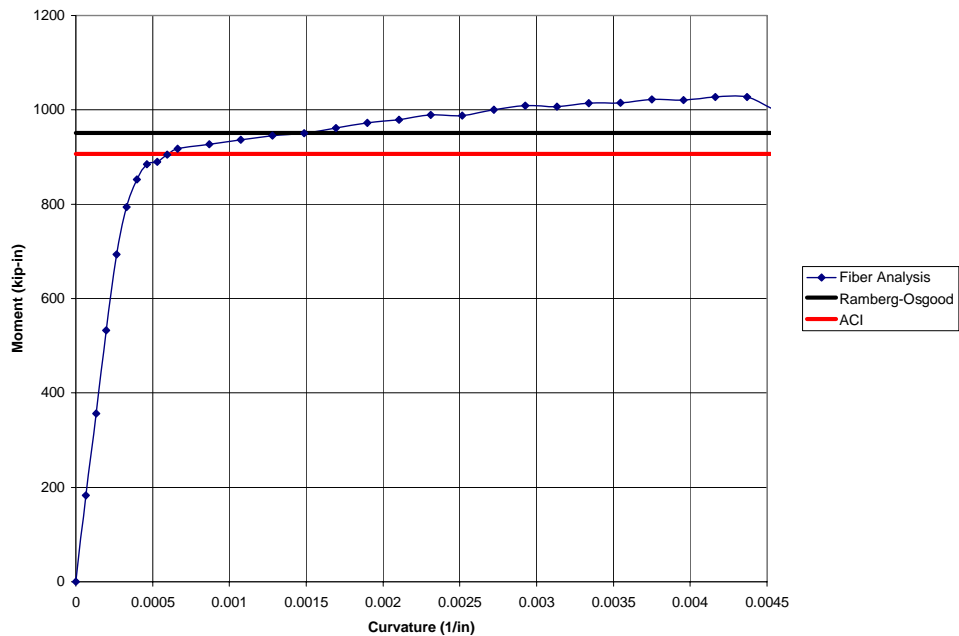


Fig. 5-2: Greater Disparity

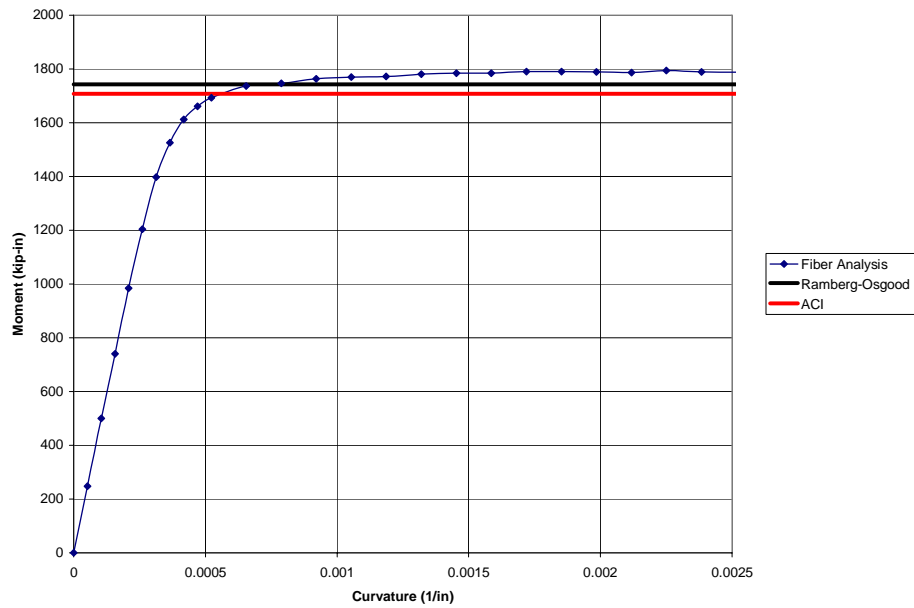


Fig. 5-3: Lesser Disparity

6. CONCLUSIONS

Since the R-O and E-PP estimates are generally conservative compared with XTRACT and within 20% of its value, this suggests that the current models are sufficient for high-strength steel. What this means is that when designing for moment capacity, the assumptions made for mild steel can simply be applied to high-strength steel.

7. RECOMMENDATIONS

Time did not allow for thorough statistical comparison between estimate methods. It is recommended that the percent differences between E-PP and Ramberg-Osgood vs. XTRACT

be compiled into a single set of data. It may be of interest to look into why a greater disparity between estimations is present in cases with minimum reinforcement. Data analysis should be done in the same fashion with T-beams as were done in this study with rectangular beams. Also, calculations should be carried out replacing grade 60 steel with high-strength steel in ACI design examples for reinforced concrete beams.

8. ACKNOWLEDGEMENTS

We would like to thank the NSF Research Experiences for Undergraduates Site in Structural Engineering: Development of Enhanced Materials and Structural Assemblages Used in Seismic Performance Evaluation Studies Grant ID No.: EEC 0552786 for funding this research project, Doctors Kukreti, Swanson, Rassati, and Shahrooz for guidance during research, and Elizabeth Ward for her invaluable knowledge and guidance in this project. We would like to give a special thanks to friend and former partner Huy Ta who was present for about half of the project's duration. Without his experience to draw upon, it would have been exceedingly difficult to get our bearings.

9. ANNOTATED BIBLIOGRAPHY

1. Bosco, C., A. Carpinteri, and P. G. Debernardi. (1990) "Minimum Reinforcement in High-Strength Concrete." *Journal of Structural Engineering*, ASCE, Vol. 106, No. 2, pp. 427-437.

This report attempts to outline a method of determining the minimum steel reinforcement for a given beam in flexure. This minimum percentage is defined as that at which the steel will reach its yielding moment under the same load that the concrete reaches its first cracking moment. The approach used was to define a number, N_p which relates beam depth, the reinforcing steel's yield strength and concrete's fracture toughness and, through testing, find the particular value for N_p . This paper was reviewed as a historic study on reinforced high-strength concrete using testing methods similar to those that we will be employing. It is assumed to have no bias, as it was included in an ASCE publication.

2. Callister, William D. (2007). *Materials Science and Engineering: an Introduction*. John Wiley & Sons, Inc.

This is a standard introductory text in materials science. The chapter, "Mechanical Properties of Metals" provides basic, yet essential, explanations of the concepts governing the reaction of metals to forces acting upon them. Also essential are the myriad definitions

of terms often encountered in the relevant literature. The text is assumed to have no bias as it is a general introductory textbook.

3. Campione, G. (2008) "Simplified Flexural Response of Steel Fiber-Reinforced Concrete Beams," *Journal of Materials in Civil Engineering*, ASCE, Vol. 20, No. 4, pp. 283-293.

The author performed experiments similar to ours, with the exception of using steel fiber-reinforcements instead of high-strength steel reinforcements. His experiments show that when referring to compressive strength and the corresponding strain, the addition of certain steel fibers has a major effect, being an increase in the ductility and postpeak resources of the material, and while referring to the strength variation and strain capacity at peak stress, a moderate increase in strength is observed.

4. Dwairi, H. Dawood, M. Rizkalla, S. and Faza S. (2004). "Shear and Flexural Behavior of Concrete Members Reinforced with MMFX Steel," North Carolina State University, MMFX Technologies Corporation.

This report contains a previous experiment which compares the usage of A615 to A1035 in actual members. Both of these materials are the main material objects studied in our research project. Therefore the information contained within this report will be extremely helpful. In the background information section of this report, it gives a well written description on the reason why A1035 has better corrosion resistance properties when compared to A615, which we will be comparing in our own research project. However, there is a conflict of interest since one of the authors works for MMFX Technologies, the producer of A1035 steel.

5. El-Hacha, Raafat, and Sami H. Rizkalla. (2002). "Fundamental Material Properties of MMFX Steel Rebars." North Carolina State University. NCSU-CFL

This report contains many mechanical properties of A1035 found through experimentation. The experimental tests conducted on A1035 steel in this project include shear, fatigue, tensile, bond strength, and compression. It will help extremely helpful as background information prior to doing any fabrication or testing of the beam members in our research project. Each of the different tests performed have their own separate section that includes test set-up and procedures. Since we will be performing a similar bend test the summary given in the report will give us a better idea about the logistics of testing. The report is not assumed unbiased since it was commissioned by MMFX Technologies Corporation to test one of their products.

6. Ramberg, W., and Osgood, W. (1943) "Description of stress-strain curves by three parameters," *National Advisory Committee for Aeronautics*, held in Seattle, Washington, July

This is the original paper in which the Ramberg-Osgood model was proposed and described. This paper was selected in order to increase familiarity with this model, and to find out how it was developed. The paper is assumed to have no bias because it is not associated with any type of product, and because its validity has been consistently demonstrated since its publication.

7. Razvi, S., Saatcioglu, M., 1999. “Confinement Model for High-Strength Concrete”, *Journal of Structural Engineering*, Vol. 125, No. 3, pp 281-289.

High-strength concrete model used for XTRACT analysis

8. Shahrooz, B., (2008) “Analysis & Design of Flexural Members” [computer file] University of Cincinnati

This is an excel file that, when given input concerning beam dimensions and steel and concrete properties determined by ACI method yield strength, Ramberg-Osgood parameters, or Mast Equation parameters, estimates moment capacity.

10. APPENDIX I: NONCLEMENTURE

- | | |
|------------------------------|---|
| 1.) Ramberg-Osgood equation: | $f_s = E_s \varepsilon_s \left\{ A + \frac{1 - A}{[1 + (B \varepsilon_s)^c]^{1/c}} \right\} \leq f_s$ |
| 2.) E_s | Steel Modulus |
| 3.) ε_s | Strain |
| 4.) f_s | Stress |
| 5.) A, B, C | Ramberg-Osgood parameters |

11. APPENDIX II: RESEARCH SCHEDULE

Week 1, 06/22-06/28: The first week will focus on preparation of our research.

- Determine model materials and parts needed
- Determine equipment needed
- Daily log written by Huy Hong Ta

Week 2, 06/29-07/05: The experimentation phase of our research will begin.

- Analytical analysis of data (Liz Ward)
- Fabrication of concrete columns for testing 07/01/08
- Testing concrete at 1 day cure strength 07/02/08
- Start the Bi-weekly report 07/01

- Literary research on usage of flexural reinforced concrete
- Daily log written by Brittany Williams

Week 3, 07/06-07/12: Continuation of experimental phase

- Analytical analysis of data (Liz Ward) completed
- Analytical analysis of data (U. Pitt) finished by end of week
- Continue to work on report for 1st experiment
- Daily log written by Heath Zumstein

Week 4, 07/13-07/19: Continuation of experimental phase

- Fabrication of flexural specimens
- Start the Bi-weekly report 07/15
- Daily log written by Heath Zumstein

Week 5, 07/20-07/26: Continuation of experimental phase

- Fabrication of flexural specimens
- Data analysis using XTRACT
- Report of 2nd experiment started
- Daily log written by Brittany Williams

Week 6, 07/27-08/02: Final processing and compilation of data

- Start the Bi-weekly report 07/29
- Begin draft of final report and presentation July 30, 2008
- Daily log written by Heath Zumstein

Week 7, 08/03-08/09: Final phase of project

- Draft of final report complete and submitted for revision on August 8, 2008
- Draft of final presentation complete
- Poster preparation
- Daily log written by Brittany Williams

Week 8, 08/10-08/14: Project Completion

- Final report revised, finalized by August 12, 2008
- Poster completed for printing on Tuesday
- Data and photos organized and burned onto CD format
- 4 copies of report printed or Xeroxed
- PowerPoint presentation completed
- Presentation will be given August 14, 2008
- Poster completed and shown August 14, 2008
- CD's of final report, all photos and data burned on separate disc for submission