Flexural Analysis and Optimized Design Software for Reinforced Concrete Beams Strengthened with NSM or Externally Bonded FRP

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Abstract

The flexural strengthening techniques of reinforced concrete beams using Externally Bonded (EB) FRP sheets or Near Surface Mounted (NSM) FRP bars have been very well established. The technology transfer has taken place into engineering design practice for two decades now through the introduction of design guidelines. However, the lack of design software in the market as well as the limited academic education of present engineers has been an obstacle against the wide spread of this technology as a preferred alternative for repair and strengthening. Recently, a US-based group has responded to this need by developing professional interactive software to analyze and design structural elements strengthened with FRP. One of the very first products that came out of this effort was the development of a detailed analysis and design tool on strengthening of RC beams. This software complies with the provisions of ACI 440.2R-17 and is available interchangeably in SI and US customary unit systems. It is capable of analyzing rectangular, T and inverted L sections strengthened with externally bonded FRP or NSM bars. It allows for one compression layer and three tension layers of steel and provides strength and serviceability calculations. It has a graphics tool for to-scale drawing of sections, and it offers a detailed professional design report. The premium version is equipped with a graphics based optimized design feature that eliminates the need to perform design iterations. Its user-friendly interface is an asset to any design office.

Keywords: Design Tools, Flexural Strengthening, RC Beams, FRP Sheets, NSM Bars.

Introduction

Flexural strengthening of reinforced concrete beams with Externally Bonded (EB) or Near Surface Mounted (NSM) Fibre Reinforced Polymer (FRP) reinforcement was first introduced in Switzerland in 1987 [Meier 1987]. Since then, the volume of research and development in this field has exponentially exploded [Triantafillou and Plevris 1992, Arduini et al. 1997, Fanning and Kelly 2001, Rasheed et al. 2006, Saqan et al. 2013, Rasheed 2014, Smith et al. 2017, Zaki and Rasheed 2021]. This was due to the success of these high specific strength materials that are lightweight, non-corrosive and easy to handle with their high future promise in this application. Accordingly, the structural engineering community responded to these expanding needs to introduce design guidelines like ACI 440.2R-17 to help provide a technical framework [ACI 440.2R-17]. On the other hand, the lack of curricula and design aids that introduce this subject in engineering education and professional design marketplace and the lack of digital design tools hindered its widespread in competing against more traditional strengthening materials. Recognizing the importance of this need, Sika® CarboDur® design software was developed based on several design guidelines including ACI 440.2R-08 [Sika USA 2021]. However, this software works more like a black box without generating detailed intermediate equations in a format of a design report. Another US-based group recently responded to this need by developing several analysis and design suites to furnish such FRP design tools with design calculations detailed in a professional report [AEDA LLC 2021]. FRP Beam Strengthening Analysis is the first of its kind software established to perform a comprehensive flexural analysis and optimized design of reinforced concrete beam sections strengthened with externally bonded FRP sheets/plates or near surface mounted FRP tape/bars to drive this technology forward with full supporting documentation. The software is available on the web for subscription-based downloads that are very affordable to the average structural engineer [AEDA LLC 2021]. Demonstration versions and educational discounts are also available to encourage students and engineers to adapt to these software advancements.

Program Features

The program user interface is composed of five different sections, see Figure 1. The first section accepts the material parameters as input. This is composed of the concrete material properties, longitudinal steel material properties and FRP material properties selected as user-defined or from the list of available properties from participating manufacturers, Figure 1a. The second section takes the geometric section parameters. This includes the section type (Rectangular, T or inverted L section), the section peripheral dimensions, internal reinforcement details for one compression and up to three tension layers, the FRP geometric parameters as well as the calculation or input of the tensile substrate concrete strain at the time of strengthening, Figure 1b. The third section is devoted to the loading calculations including but not limited to the sectional dead load moment, the sectional live load moment at the time of strengthening (constructional live load moment) and the upgraded live load moment. This section also furnishes the calculation of the ultimate section moment under the upgraded live loading if the FRP should be lost, the service moment and the ultimate upgraded moment with FRP, Figure 1c. The fourth section provides the to-scale drawing utility as well as the action item buttons to plot or clear the section, to perform optimized design or just section analysis, to print a screen shot or generate the comprehensive design report, Figure 1d. The fifth section is left for the results when activating the "Analysis" button including the final strain profile of the strengthened section, key output results as well as a comprehensive list of strength values and serviceability checks, Figure 1e.

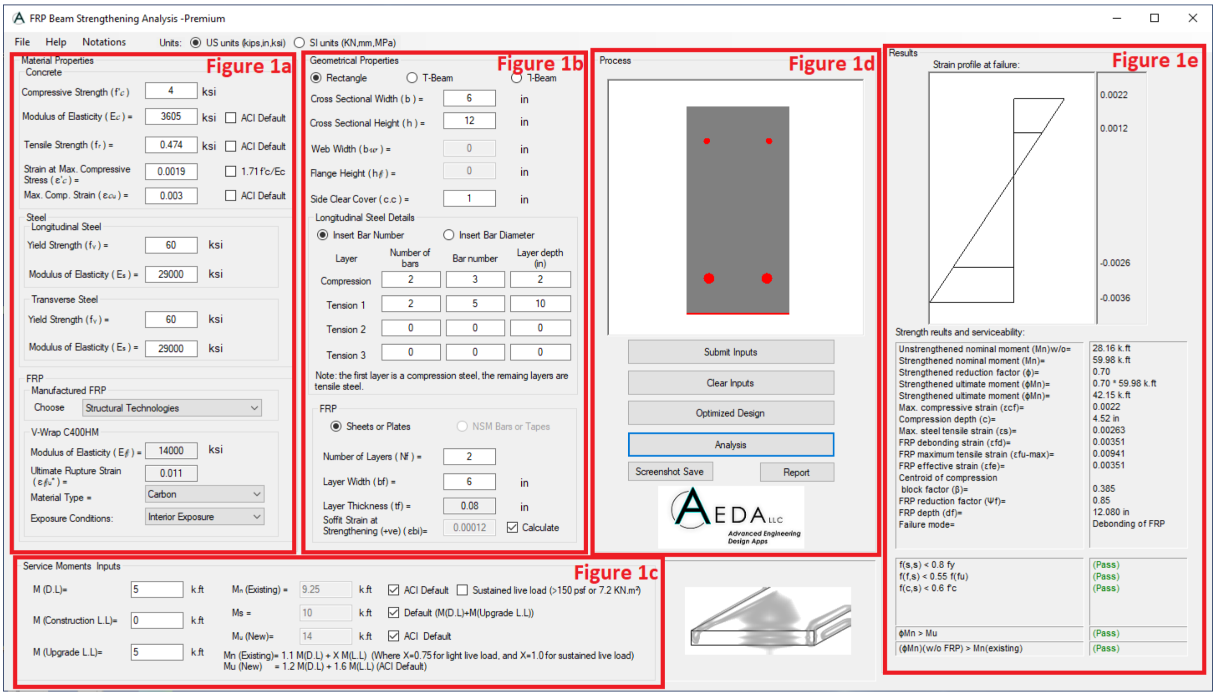

Figure 1. Graphics User Interface for FRP Beam Strengthening Software.

Analytical Formulations

The developed program, in its current version, is built upon a completely analytical engine that solves quadratic equations or cubic expressions converted into equivalent quadratic equations with explicit determination of the neutral axis depth for each failure mode involved, namely, FRP rupture, concrete crushing and FRP debonding. For each failure mode, eight sets of closed form equations are established to control the specific eight cases involved:

1. All three tension layers yield, and compression layer does not yield.
2. Two extreme tension layers yield, and compression layer does not yield.
3. Only the extreme tension layer yields, and compression layer does not yield.
4. No tension layer yields, and compression layer does not yield.
5. All three tension layers yield, and compression layer also yields.
6. Two extreme tension layers yield, and compression layer also yields.
7. Only the extreme tension layer yields, and compression layer also yields.
8. No tension layer yields, but compression layer yields.

The force equilibrium equation is explicitly solved for the neutral axis depth of each of the eight possible cases in a specific failure mode. Based on the steel strains from the generated strain profiles in terms of the failure mode strain and neutral axis depth found, the applicable single case is selected. This is repeated for all three controlling failure modes and the lowest FRP strain associated with all three failure modes identifies the dominant mode for this analysis. Once the dominant failure mode is extracted, the corresponding moment capacity and the related parameters are finalized. At this point, the program generates the professional report based on the controlling failure mode and all input, relevant equations and output results impacted. This is made available in a pdf file format for the engineer to follow and check the calculations.

To showcase a sample of the analytical equations developed, the failure mode of concrete crushing for rectangular strengthened RC sections is presented below:

Case 1: $0.85\, f'_c b\beta_1 c + A'_s E_s \varepsilon'_s - A_{s1} f_y - A_{s2} f_y - A_{s3} f_y - A_f E_f \varepsilon_{fe} = 0$

Case 2: $0.85\, f'_c b\beta_1 c + A'_s E_s \varepsilon'_s - A_{s1} f_y - A_{s2} f_y - A_{s3} E_s \varepsilon_{s3} - A_f E_f \varepsilon_{fe} = 0$

Case 3: $0.85\, f'_c b\beta_1 c + A'_s E_s \varepsilon'_s - A_{s1} f_y - A_{s2} E_s \varepsilon_{s2} - A_{s3} E_s \varepsilon_{s3} - A_f E_f \varepsilon_{fe} = 0$

Case 4: $0.85\, f'_c b\beta_1 c + A'_s E_s \varepsilon'_s - A_{s1} E_s \varepsilon_{s1} - A_{s2} E_s \varepsilon_{s2} - A_{s3} E_s \varepsilon_{s3} - A_f E_f \varepsilon_{fe} = 0$

Case 5: $0.85\, f'_c b\beta_1 c + A'_s f_y - A_{s1} f_y - A_{s2} f_y - A_{s3} f_y - A_f E_f \varepsilon_{fe} = 0$

Case 6: $0.85\, f'_c b\beta_1 c + A'_s f_y - A_{s1} f_y - A_{s2} f_y - A_{s3} E_s \varepsilon_{s3} - A_f E_f \varepsilon_{fe} = 0$

Case 7: $0.85\, f'_c b\beta_1 c + A'_s f_y - A_{s1} f_y - A_{s2} E_s \varepsilon_{s2} - A_{s3} E_s \varepsilon_{s3} - A_f E_f \varepsilon_{fe} = 0$

Case 8: $0.85\, f'_c b\beta_1 c + A'_s f_y - A_{s1} E_s \varepsilon_{s1} - A_{s2} E_s \varepsilon_{s2} - A_{s3} E_s \varepsilon_{s3} - A_f E_f \varepsilon_{fe} = 0$

The eight equations above are all quadratic in terms of the depth of neutral axis (c) and may be solve explicitly for a specific value of (c). Once (c) is determined, it is used along with the extreme compression fibre strain of 0.003 to establish the strain profile to each viable case. The correct case is the one that has the strain in all four layers of steel matching the case that generated its strain profile. There can be only one admissible case to achieve equilibrium under the four conditions specified.

Optimized Design Option

For the specific beam cross section material and geometric parameters entered, the user may choose to generate the complete set of possible analysis solutions and plot that as a curve relating the number of FRP EB sheets or the number of FRP NSM bars on the x-axis against the ultimate moment furnished on the y-axis. By specifying the actual ultimate moment targeted for strength only, an optimum (minimum) quantity of FRP is computed to fulfill that desired moment, see Figure 2-3. A comprehensive tabulated list of all possible designs can be invoked to provide the specific results in numbers, Figure 4. On the other hand, this extracted strength-based optimum design may not satisfy the serviceability limits. Therefore, an option to consider both the strength and serviceability requirements is made available. In this case, four different curves are plotted and the highest horizontal line representing strength and stress limit is concrete, steel and FRP is chosen as the optimum design case that satisfies every condition.

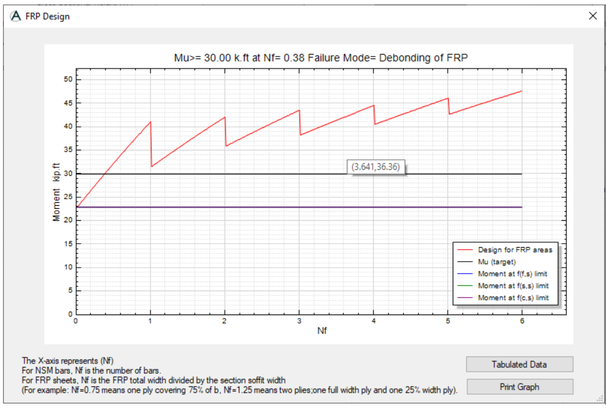

Figure 2. Optimized Design Graph for EB Sheets.

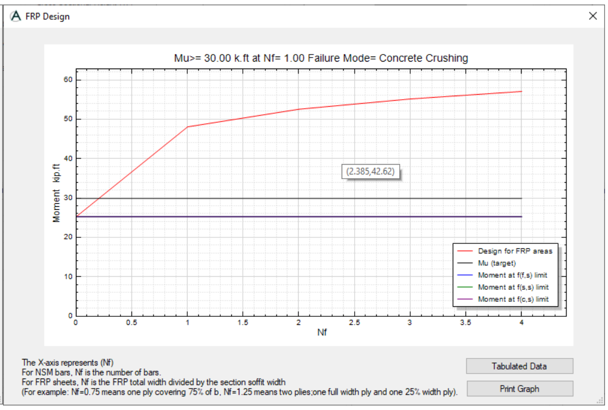

Figure 3. Optimized Design Graph for NSM Bars.

FRP Ratio

Nf	FRP Area (Af)	φMn	φ	Mn	ε_{fe}	ε_{cf}	ε_{st}	c
0.01	0.006	22.95	0.81	28.19	0.00496	0.00142	0.00397	2.63
0.02	0.012	23.2	0.81	28.5	0.00496	0.00143	0.00397	2.65
0.04	0.018	23.34	0.81	28.79	0.00496	0.00144	0.00393	2.68
0.05	0.024	23.68	0.81	29.1	0.00496	0.00145	0.00396	2.68
0.06	0.03	23.93	0.81	29.41	0.00496	0.00146	0.00396	2.69
0.08	0.036	24.18	0.81	29.72	0.00496	0.00147	0.00396	2.71
0.09	0.042	24.42	0.81	30.03	0.00496	0.00148	0.00396	2.72
0.1	0.048	24.56	0.81	30.31	0.00496	0.00149	0.00392	2.75
0.11	0.054	24.9	0.81	30.62	0.00496	0.0015	0.00396	2.75
0.12	0.06	25.14	0.81	30.93	0.00496	0.00151	0.00395	2.77
0.14	0.066	25.39	0.81	31.24	0.00496	0.00152	0.00395	2.78
0.15	0.072	25.63	0.81	31.54	0.00496	0.00153	0.00395	2.79
0.16	0.078	25.88	0.81	31.85	0.00496	0.00154	0.00395	2.8
0.17	0.084	26.01	0.81	32.13	0.00496	0.00155	0.00391	2.83
0.19	0.09	26.35	0.81	32.44	0.00496	0.00156	0.00395	2.84
0.2	0.096	26.59	0.81	32.75	0.00496	0.00157	0.00394	2.85
0.21	0.102	26.84	0.81	33.05	0.00496	0.00158	0.00394	2.86
0.22	0.108	27.08	0.81	33.36	0.00496	0.00159	0.00394	2.87

Figure 4. All Possible Designs Tabulated for a Beam Strengthened with EB Sheets

Results and Discussion

To illustrate the program functionality, example 16.3 of ACI 440.2R-17 is replicated here. The design example assumes two layers of CFRP sheets to be applied then checks the target moment against the furnished moment and performs all the serviceability limits, Figure 5. This is basically turning the design problem into an iterative analysis process. The converged iteration is selected here to analyze resulting in a perfect match with the example results.

Furthermore, the optimized design option is invoked next to extract the minimum FRP quantity needed to satisfy both the strength and serviceability target requirements. The solution reveals the fact that only 80% of a single sheet is needed to fulfill all requirement of the design instead of the full two sheets selected in the ACI 440.2R-17 example 16.3, Figure 6.

By re-analyzing the beam using the optimum size of FRP, it is confirmed to fulfill the needed limits of the guidelines. This exercise illustrates the power of the present software in avoiding the application of manual or spreadsheet-based iterations yielding optimized design output. It will further contribute to the efficiency of the design process and guarantees the economy of the material and labor cost involved.

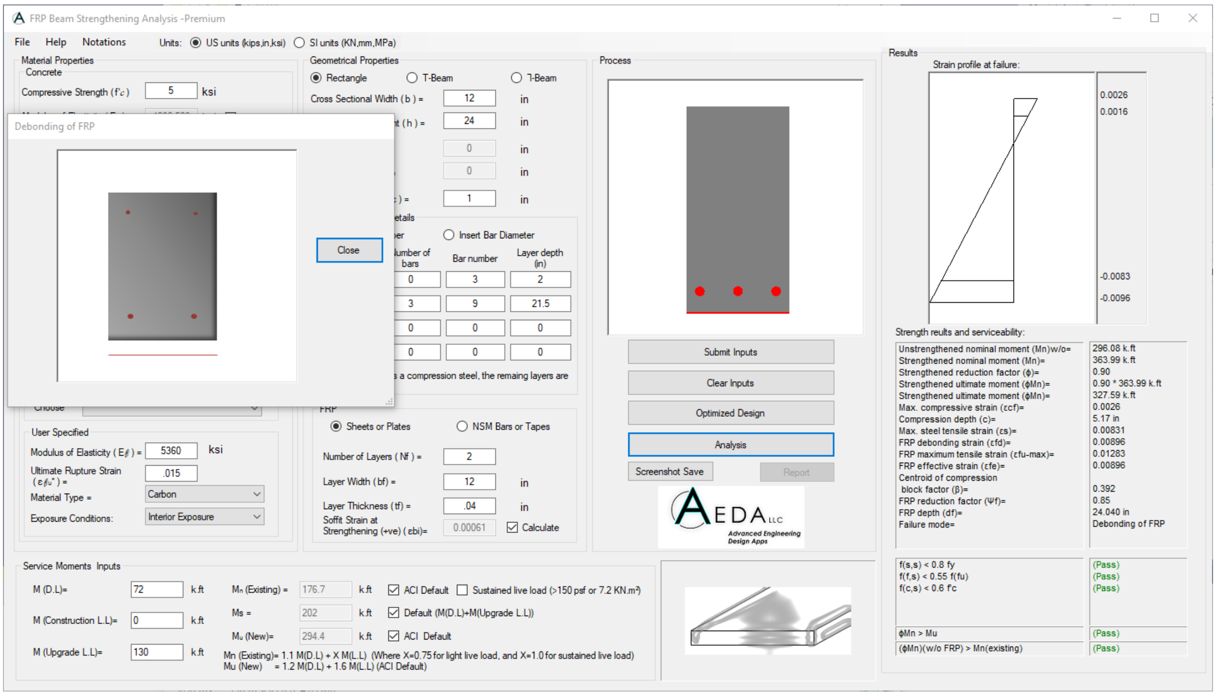

Figure 5. Analysis of Example 16.3 of ACI 440.2R-17.

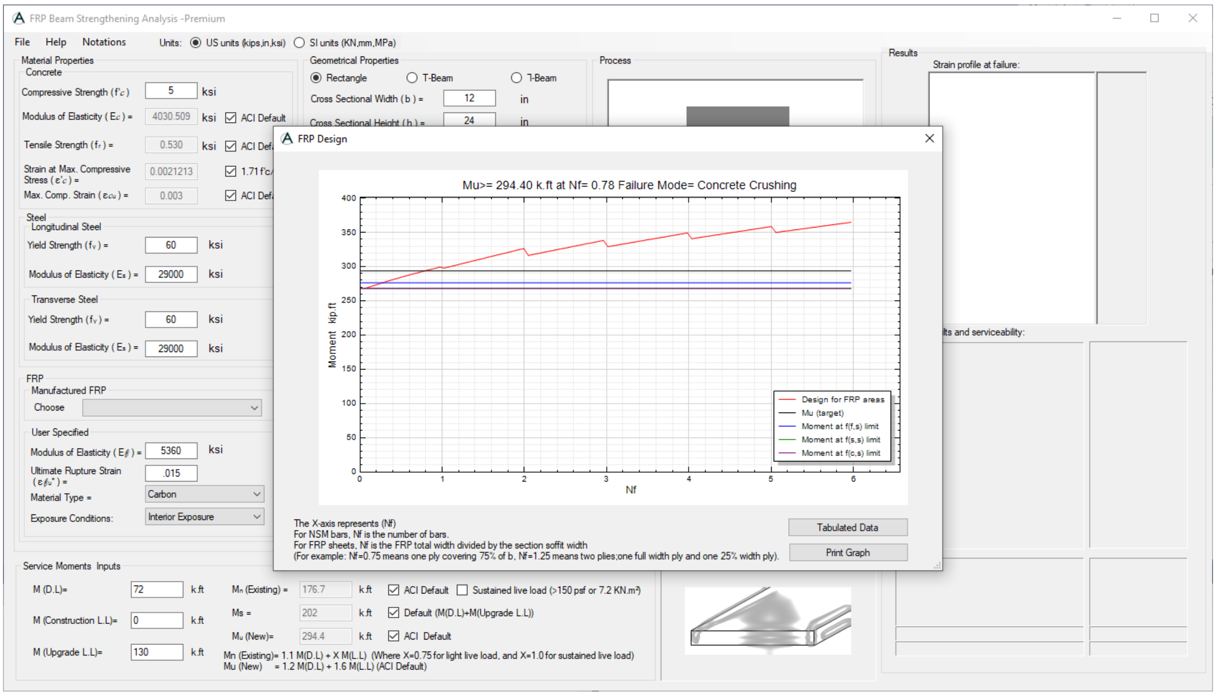

Figure 6. Optimized Design for Example 16.3 of ACI 440.2R-17 for Strength and Serviceability.

Conclusions

A powerful design tool was developed for the strengthening of RC beam sections with externally bonded FRP sheets and plates as well as near surface mounted FRP bars and tape. The software is governed by the limit states admitted by the ACI 440.2R-17 and provides the engineer with flexibility and cost savings when performing the optimized design options. It is supplemented with a graphics drawing tool to show to scale sketches where users may visually catch their possible input mistakes. A fully detailed design report is also provided showing all input parameters, intermediate analysis equations and output results for a complete documentation of the generated designs. The full toggling between the US customary and SI units is another favourable feature of this efficient software.

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