UNIVERSITY OF MICHIGAN

REPAIR AND STRENGTHENING OF REINFORCED CONCRETE BEAMS USING CFRP LAMINATES

Task 9: Computer Program

by

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16. Abstract

This computer program provides failure load, failure mechanism, maximum moment and shear values, deflection at mid span, as well as moment-curvature and stresses for any cross section of a reinforced concrete beam strengthened by an externally bonded CFRP laminate subjected to a predefined loading configuration.

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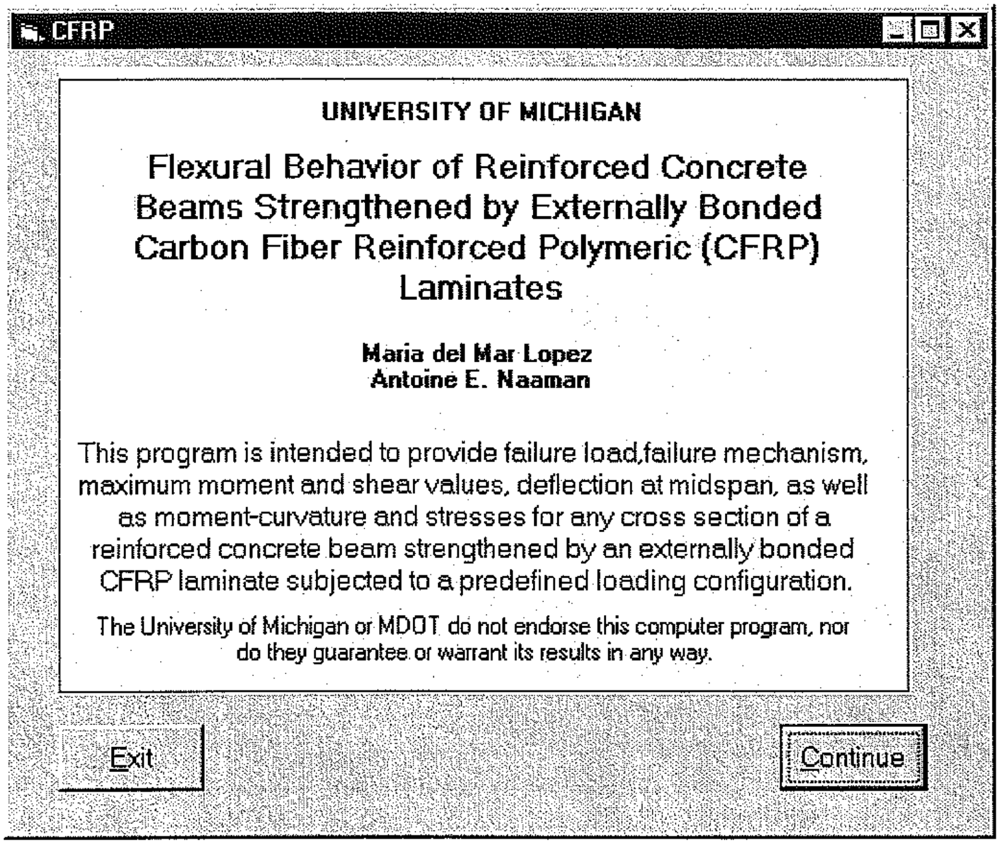

USER'S MANUAL

This program is intended for the analysis of simply supported reinforced concrete beams strengthened by externally bonded Carbon Fiber Reinforced Polymeric (CFRP) Laminates. The use of the information provided by this program for the design of strengthening systems is the sole responsibility of the user. The University of Michigan or MDOT do not endorse this computer program, nor do they guarantee or warrant its results in any way.

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1 INTRODUCTION

This program provides failure load, failure mechanism, maximum moment and shear values, deflection at mid span, as well as moment-curvature and stresses for any cross section of a reinforced concrete beam strengthened by an externally bonded CFRP laminate subjected to a predefined loading configuration.

SI units are used. This program has the capacity to analyze a reinforced concrete beam with up to 10 layers of longitudinal steel (area, location and depth are specified for every layer of steel), up to five different types of stirrups (total area, spacing and location are particular for specified type of stirrup), see Figure 1.

To model the behavior of concrete in compression, Hognestad's concrete model is used [1]. The tensile properties of concrete can be also considered, otherwise a default value of zero for the tensile strength is considered. For the longitudinal steel, an option for strain hardening is included, otherwise the steel is modeled as a linear-elastic perfectly plastic material. The CFRP laminate is modeled as a linear elastic material.

The **Moment-Curvature Option** produces a moment-curvature curve of a cross section of a reinforced concrete beam strengthened by an externally bonded CFRP laminate. For this, a step by step strain compatibility analysis is obtained, where the location of the neutral axis is carried out through an iterative process where equilibrium of internal forces is satisfied [2], [3]. Eighty (80) pairs of points (moment,curvature) are used to build the moment-curvature curve. The user also has the option to request a particular point. For every pair of points, strains, stresses and forces are calculated at every layer of cross section. A plot of the moment-curvature can be obtained as well as selected points of interest for the user.

The values for the 80 points used to build the moment-curvature are recorded and stored in a file. Strains in the top compression layer are also recorded, as well as the total force in the concrete; strains and forces in the CFRP and strains and stresses at every layer of longitudinal steel are also included. A summary of the input data is also stored in file.

The **Beam-Analysis Option** analyses a simply supported reinforced concrete beam strengthened by an externally bonded CFRP laminate. For loading, the user can choose between incremental loads (uniform distributed load, 1 point load, and two-point load) or AASHTO live loads. For each particular load configuration, 10 sections (at every 1/10 of the half span) are analyzed. The user has the option to request a section located at any particular ordinate along of the span. The AASHTO load can also be specified with a magnification coefficient. External moment and shear values are calculated at every section.

Dead loads are considered as uniform loads applied over the total beam span. They are calculated based on the beam cross sectional area and the concrete unit weight input by the user.

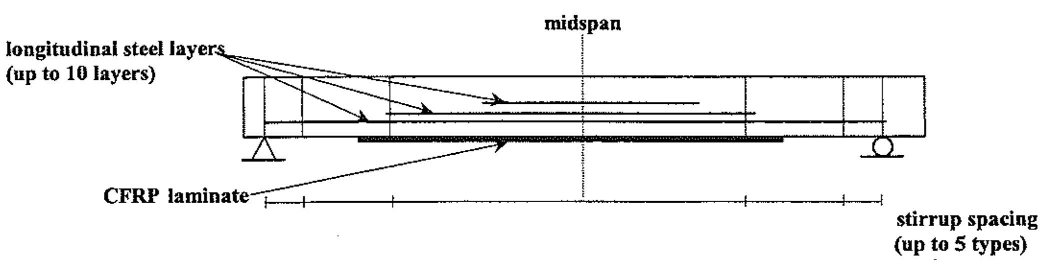
This program assumes that there is no preexisting load before the CFRP laminate is applied to the reinforced concrete beam. It is considered that this assumption does not modify the capacity at ultimate of the reinforced concrete beam strengthened by an externally bonded CFRP laminate.

As output, a table is produced including all the results that are considered to be of interest to the user. If the option AASHTO loads is selected in the load window, the table of results include the following values: unfactored moment and shear values from external live load (Mexternal, Vexternal) as well as factored moment and shear values (Mu, Vu); reduced values such as maximum internal moment (Mmax); shear capacity of the section (Vmax); cracking moment (Mcracking); moment at steel yield (Msteelyield); moment when rupture of CFRP laminate occurs before (MCFRP rupt. 1) or after (MCFRP rupt. 2) the compression concrete failure; moment at compression concrete crushing (M Compression); moment at steel rupture (M steel rupture); and moment when interfacial stresses are higher than the shear stress of concrete (Minterfacial).

If the option incremental loads is selected in the load window, all the shear and moment values presented in the table of results are unfactored.

Additionally the program indicates the value of deflection at the midspan and the location, value and type of failure for the critical section. For the critical cross section, strains in the top compression layer are also recorded, as well as total the force in the concrete; strains and forces at the CFRP and strains and stresses at every layer of longitudinal steel are also included. A summary of the input data is also presented.

Figure 1. Beam configuration



1.1 Hardware requirements

This program was written using Visual Basic v6.0 for the Windows 95/98 and NT 4.0 (service pack 3 or later) operating systems, and has the following basic hardware requirements:

- IBM PC (or compatible) with Intel Pentium type CPU.
- 16 MB of RAM memory
- 2 MB free space on your hard disk
- monitor and graphics that can ensure a minimum resolution of 640 x 480 pixels (color).
- To utilize the "print" option, a printer should be attached to the LPT1 port.

1.2 Program installation

This computer program should be installed running the file "setup.EXE" included in the zip disk labeled "CFRP program". The setup wizard will guide you through the process of installing the executable file "CFRP program". The source code of the program is also included in the zip disk. It can be viewed using Visual Basic v6.0 or later.

1.3 Running the program

To run the program you can either run the "CFRP program" located under **Programs** from the **Start** menu, or you can choose the **Run** command from the **Start** menu and using **Browse** select the file "CFRP program.EXE".

1.4 Exiting the program

Exit the program by choosing the **Exit** command from the **File** menu or by clicking the **Exit** button that appears on selected windows. This will end the program and return to the windows platform. **Remember:** if you exit BEFORE **saving** your results, you will not have a results file.

1.5 Continue and Back buttons

The **Continue** button appears in all the windows of the program. By clicking this button, the program activates the next window. The **Back** button allows the user to go back one (1) window to review or reenter data.

2 SYMBOLS AND ABBREVIATIONS

Table 1. Symbols and abbreviations

Symbol	Units	Default Value	Description
A1	[mm^2]	142	Total area of stirrups 1
As1	[mm^2]	400	Area of steel layer #1
B	[mm]	100	Width of the web
bbf	[mm]	0	Width of the bottom flange, for rectangular sections bbf=0
bCFRP	[mm]	100	Width of the CFRP laminate
btf	[mm]	0	Width of the top flange, for rectangular sections btf=0
DF	-	1	Load distribution factor
DL	-	1.25	Dead load factor
Ec	[MPa]	*	Elastic modulus of concrete
ECFRP	[MPa]	228000	Modulus of elasticity of CFRP laminate
eco	[%]	0.3	Peak compression strain of concrete
ecu	[%]	0.6	Maximum compression strain of concrete
erupt	[%]	0.12	Strain at rupture of steel
Esh	[MPa]	*	Modulus of the strain hardening branch of steel
esh	[%]	*	Strain at the onset of strain hardening
Et	[MPa]	*	Tensile modulus of elasticity of concrete (if ft $\neq$ 0)
etu	[%]	*	Maximum tensile strain of concrete
Ey	[MPa]	20000	Elastic modulus of steel
f'c	[MPa]	55.2	Peak compression stress of concrete (compressive strength)
FCFRP	[MPa]	3480	Ultimate strength of CFRP laminate
ft	[MPa]	*	Tensile strength of concrete
fy	[MPa]	414	Yield strength of the longitudinal steel
fys	[MPa]	505	Yield strength of the steel stirrups
h	[mm]	300	Total height of the beam
hbf	[mm]	0	Depth of the bottom flange, for rectangular sections hbf=0
htf	[mm]	0	Depth of the top flange, for rectangular sections htf=0
I	-	0.3	Impact coefficient
l1	[mm^2]	s	Length of the steel layer #1, assumed centered over the span
lCFRP	[mm]	s	Length of the CFRP laminate, centered over the span
LL	-	1.75	Live load factor
RF	-	1	Reduction Factor
s	[m]	2.7	Span between supports
S1	[mm]	200	Spacing of stirrups 1
tCFRP	[mm]	0.34	Thickness of the CFRP laminate
uw	[kN/m^3]	23.6	Unit weight of concrete
x1	[m]	s	Distance from center of support to the end of the spacing of stirrup1
y1	[mm]	250	Distance of steel layer #1 from the extreme top fiber of the beam
Z	-	150	Slope of the descending branch of compression model of concrete
Zt	-	*	Slope of the descending branch of tension model of concrete

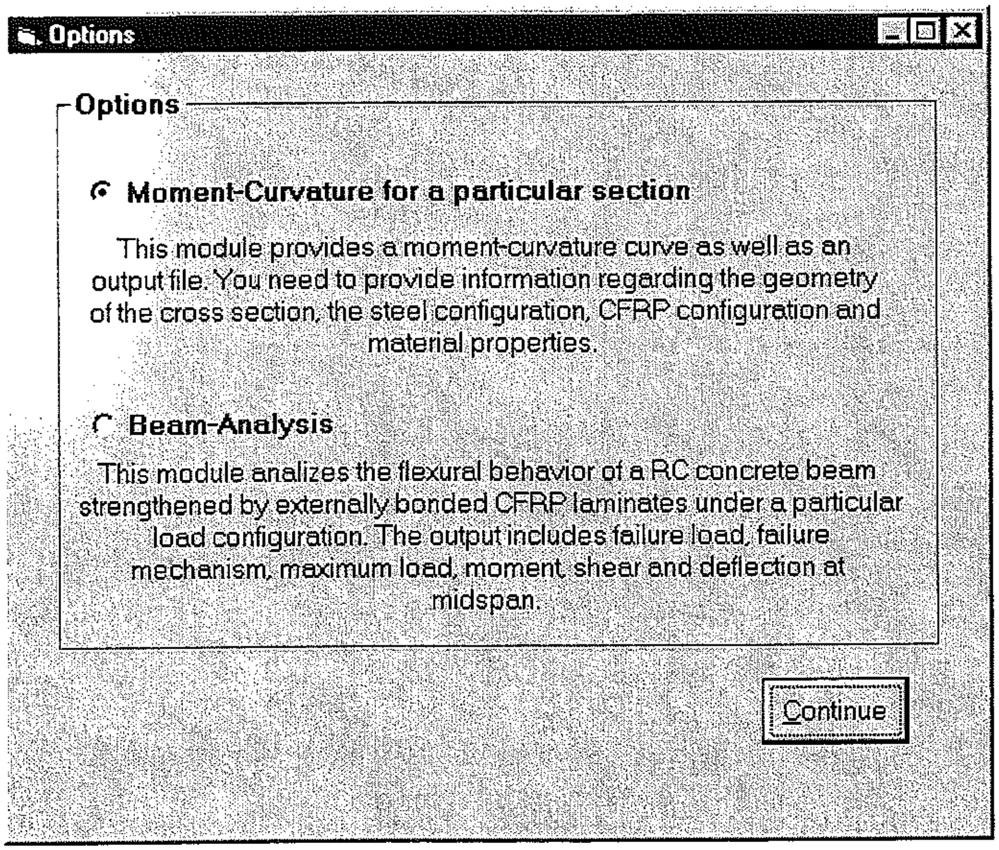
Note: * depends on the option selected by the user

3 CONFIGURATION OF THE PROGRAM

3.1 Options

By selecting the option **Moment-Curvature**, the program allows the user to produce a moment-curvature curve of a cross section of a reinforced concrete beam with (or without) a CFRP laminate.

The option **Beam-Analysis** does section analysis at every 0.05 of the span length. The user gets the moment capacity of the section as well as moment at particular points (yielding of steel, crushing of concrete, CFRP rupture, interfacial stress between CFRP and concrete exceeding the shear strength of the concrete, etc).



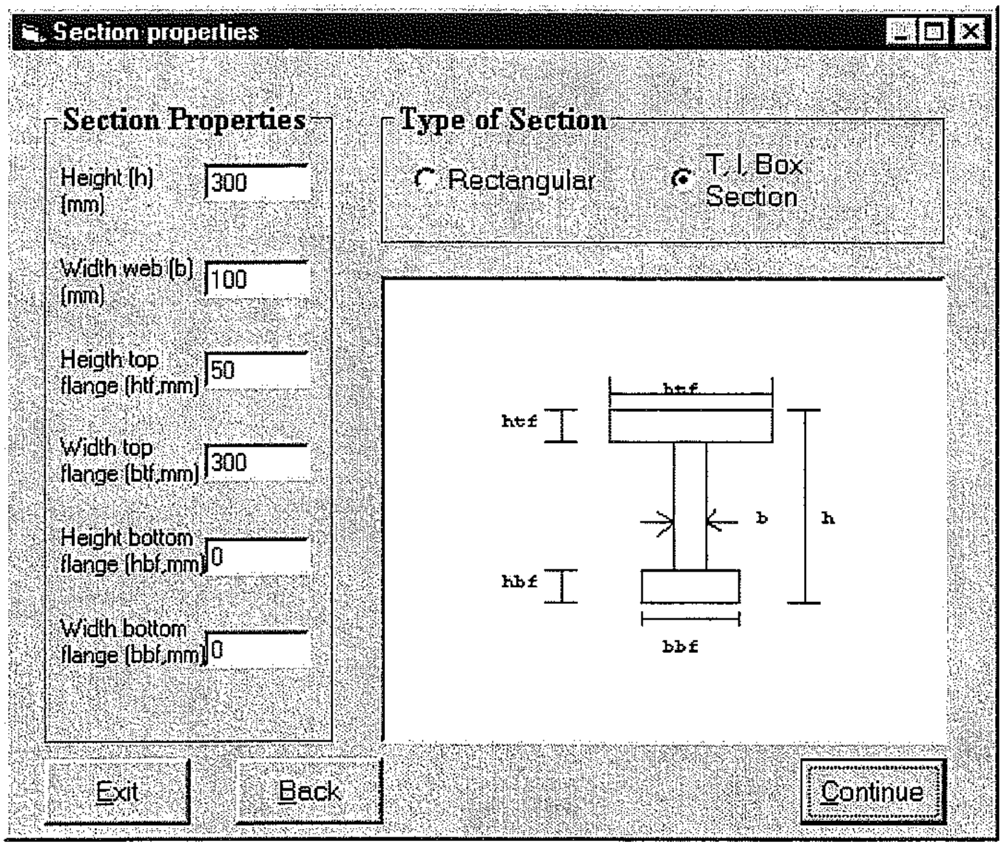
3.2 Moment-Curvature

3.2.1 Input data

3.2.1.1 Section Properties

The geometric properties of the cross section of the beam to be analyzed are entered here.

The user should select first the type of section: a) **Rectangular**; b) **T,I, Box Section**.
If **Rectangular** is selected, only boxes for height (h) and width of the web (b) will be active. If **T,I, Box Section** is selected, all the other options height of the top flange (htf), width of the top flange (btf), height of the bottom flange (hbf), width of the bottom flange (bbf) are available as well. For the **Box Section** option, the user should enter the total width of the web (b), e.g. the sum of the widths of both webs.



3.2.1.2 Material properties

Material properties for the concrete, steel and CFRP laminate are entered here.

To model the behavior of the concrete in compression, the computer program uses Hognestad's concrete model [1], see appendix A. The user enters the values for peak compressive stress (f'c), Elastic modulus of elasticity (Ec), peak compression strain (eco), slope descending branch (Z) and maximum compression strain (ecu). Default values are presented on Table 1. If the value of Ec is not modified by the user, the program assumes a default value as follows: Under the option **Moment-Curvature** Ec = 4730 $\sqrt{f'c}$ (MPa, no concrete unit weight is considered). Under the option **Beam-Analysis** Ec = 0.043 $\gamma^{1.5}$ $\sqrt{f'c}$ by default (γ = uw, unit weight of the concrete in kN/m^3).

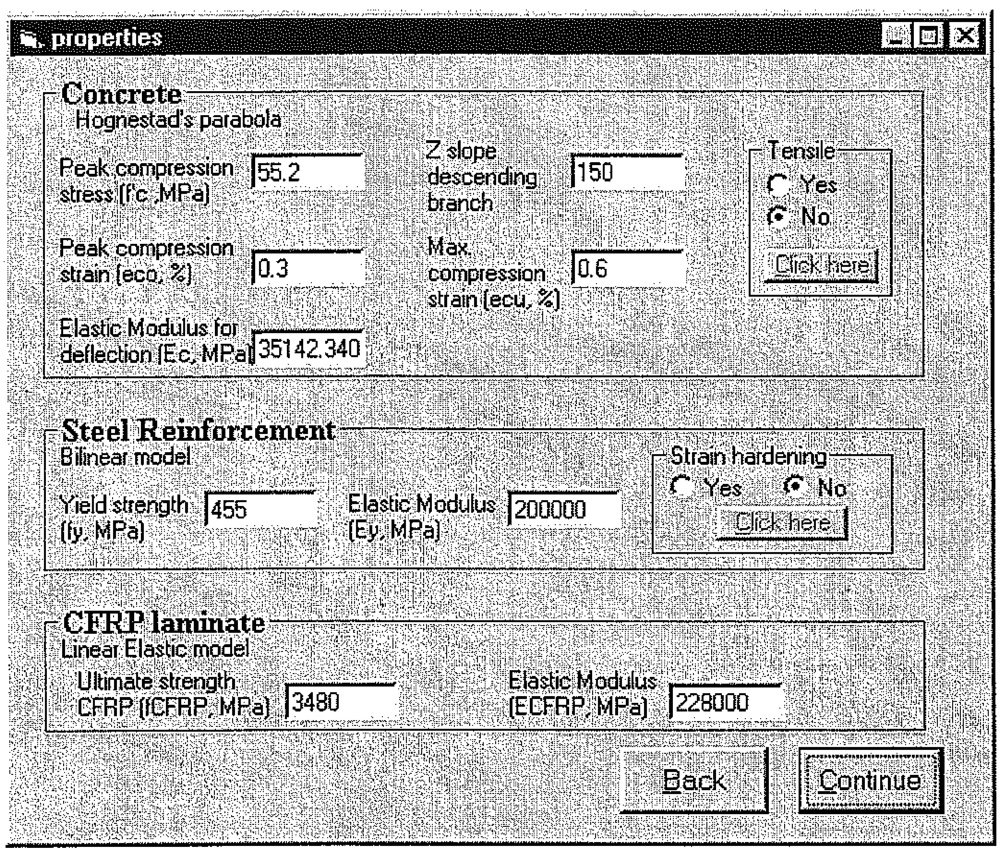
If the option **Tensile**, is selected, the tensile properties of the concrete will be considered, otherwise the tensile strength of concrete (ft) is taken equal to 0.62 $\sqrt{f'c}$ for the uncracked section and is taken as zero after the section reaches the cracking stage. The behavior of the concrete in tension is modeled with a linear ascending and descending branch, see appendix A. The user enters the values for ft, Et, Zt and etu. This option should be used at the discretion of the user. See reference [4] for further information.

In order to obtain a moment capacity analogous to the ACI or AASHTO equivalent stress block [5] use eco=0.3 and **Tensile** option = no.

For the longitudinal steel, a linear-elastic perfectly plastic model is used, see appendix A. The user enters the values for yield strength (fy) and elastic modulus (Ey). If the option **Strain hardening** is selected, the model is modified into a bilinear model with a strain-hardening branch, see appendix A. The user enters the values for strain at the onset of the strain hardening (esh), Modulus of the strain hardening branch (Esh) and strain at rupture (erupt). This option should be used at the discretion of the user. See reference [6] for further information.

The CFRP laminate follows a linear behavior up to tensile failure, see appendix A. The user enters the values for ultimate strength of the CFRP laminate (fCFRP) and Elastic modulus (ECFRP). Default values of the above variables are indicated on Table 1.

The epoxy is considered not to contribute to the flexural capacity of the section. Therefore, no material properties are considered for these calculations. A perfect bond is assumed between the CFRP laminate and the concrete.



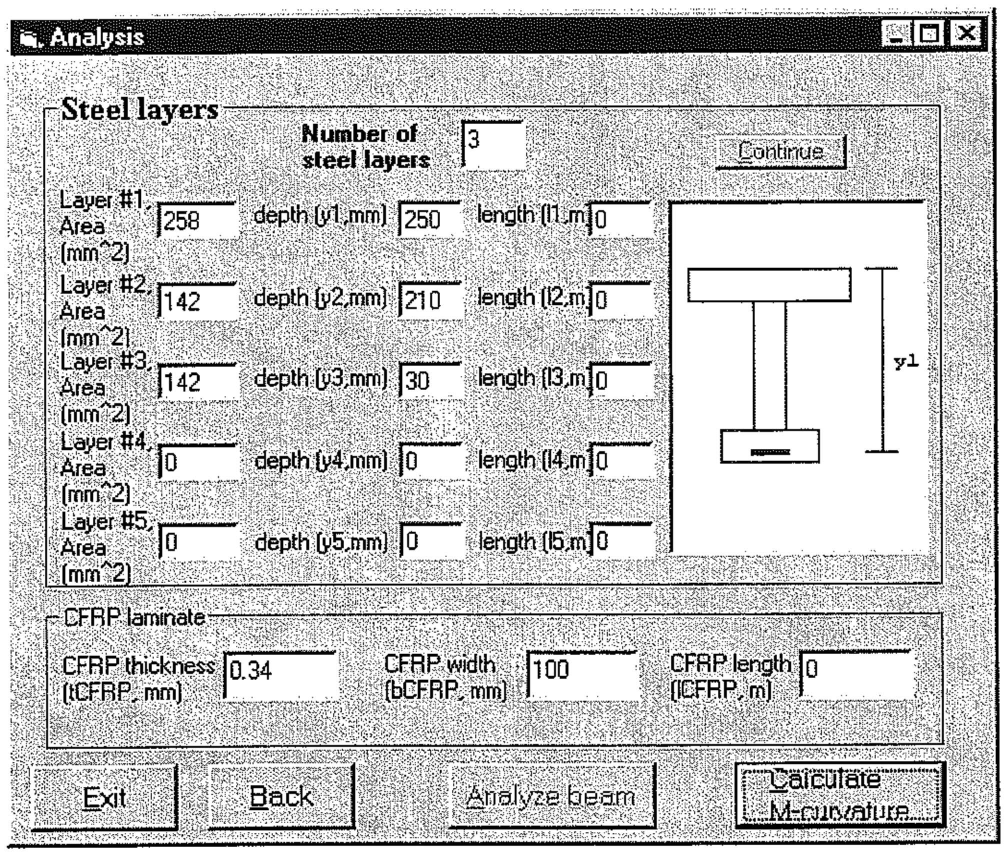
3.2.1.3 Steel and CFRP laminate configuration

For the steel configuration, the user enters the number of steel layers (up to 10), see Figure 1. For every layer, area (Asi), distance from top of beam (yi), and length (li). The value of the length is activated only if the user is in option **Beam-analysis**, otherwise the length is not considered (section analysis). Longitudinal steel layers are centered over the span. If the number of steel layers is greater than 5, click the button **Continue** next to number of layers to fill the information for the additional layers of steel.

For the CFRP configuration, the user enters thickness (tCFRP) and width (bCFRP) of the CFRP laminate. The CFRP is placed at the bottom of the concrete beam and centered within the width of the concrete beam, see Figure 1. The length (lCFRP) of the CFRP should be entered if the user is in option **Beam-analysis.** The length is centered over the span. If the section being analyzed doesn't have a CFRP laminate, set the thickness (tCFRP) equal to zero.

If user is in option **Moment-Curvature**, click button **Calculate M-curvature** to obtain the moment-curvature curve.

If the user is in option **Beam-analysis**, by clicking the button **Analyze beam** a section analysis every 0.05 of the length is obtained. If the user clicks the button **Calculate M-curvature,** the moment-curvature curve for the cross section at the midspan will be calculated.

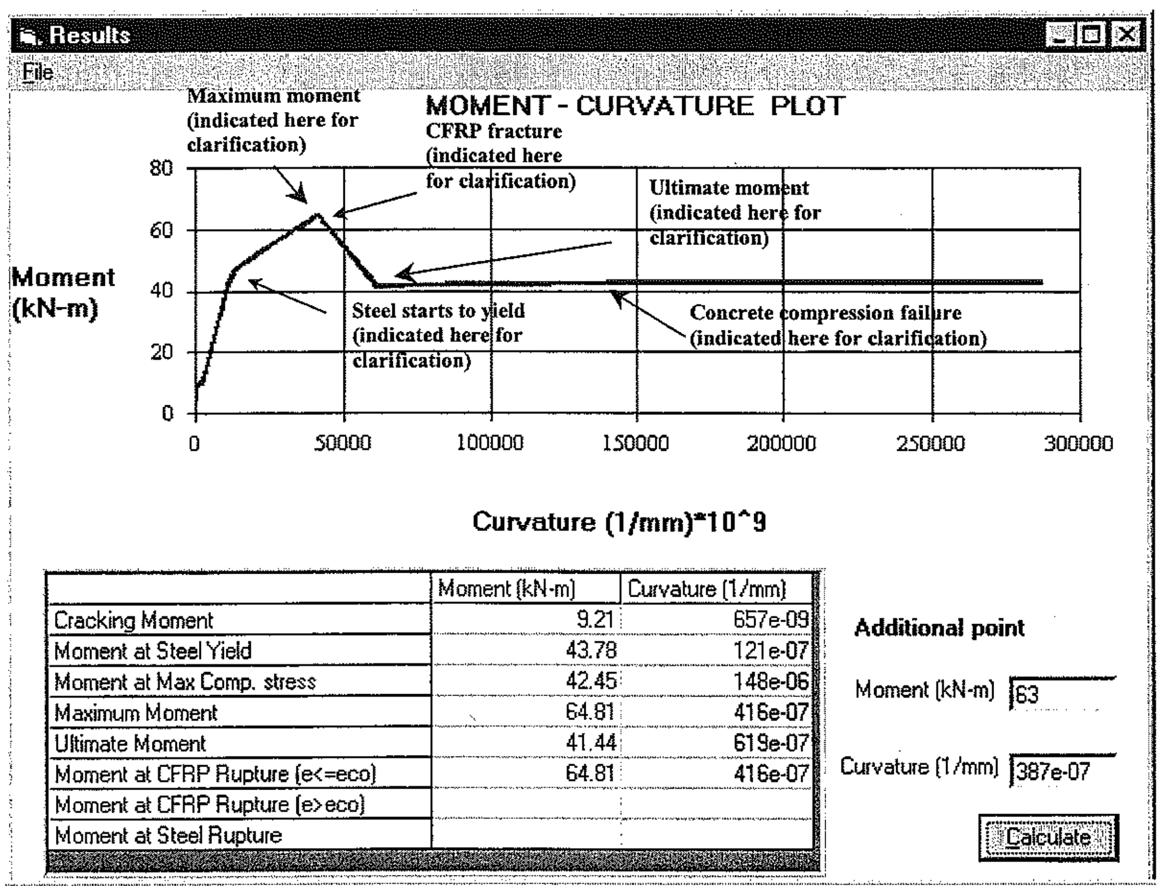


3.2.2 Calculations

To calculate the points of the moment-curvature curve, a step by step strain compatibility analysis is carried out, where the location of the neutral axis is obtained through an iterative process where equilibrium of internal forces is satisfied [2]. Eighty points (moment, curvature) are used to build the moment-curvature curve. For every pair of points, strains, stresses and forces are calculated at every layer of cross section.

3.2.3 Output data

The results window shows a plot of the moment-curvature curve. Selected values of moment and curvature are presented in a table below the graph: cracking moment (Cracking Moment); moment at steel yield (Moment at Steel Yield); moment at compression concrete crushing (Moment at Max. Comp. Stress); maximum value of moment capacity (Maximum Moment); ultimate moment value (Ultimate Moment) which corresponds to the point when the moment capacity of the section drops 30% from the maximum value or when the total number of iteration points (80) have been completed, which ever is first; moment when rupture of CFRP laminate occurs before compression concrete failure (e≤eco); moment when rupture of CFRP laminate occurs after compression concrete failure (e>eco); and moment at steel rupture (M steel rupture).



The user should select which of the above failure criteria should govern his/her design. The option **Additional point** allows the user to find the corresponding curvature for a particular value of moment. The user should input the value of moment and click the button **Calculate**. Under the **File** menu, the user can choose to **Save Results** in a file (input data are included), **Print the form** "Results" (to the printer attached to the LPT1 port) or **Exit** the program. Exiting the program DOES NOT automatically save results.
As output data the user obtains a summary of the input data and output data. The values at the 80 points used to built the moment-curvature are recorded, that is: strains in top compression layer, as well as total force in concrete; strains and forces at the CFRP; and strains and stresses at every layer of longitudinal steel.

3.3 Beam-Analysis

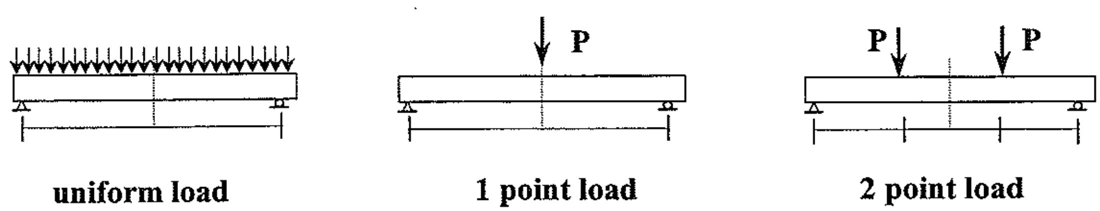
3.3.1 Input data

3.3.1.1 Load Configuration

Enter value of span between supports (s) and concrete unit weight (uw). In this window the user selects what type of load configuration will be used: incremental loads or AASHTO loads.

For the incremental load, the user can choose among **Uniform distributed load, 1 point load** (load placed at midspan) or **2 point load** (enter span between loads, span should be smaller than the span between supports). See Figure 2 below. The computer program will calculate internally (there is no input window) the smallest value of external load (in addition to self-weight) that leads to any type of failure at any section considered.

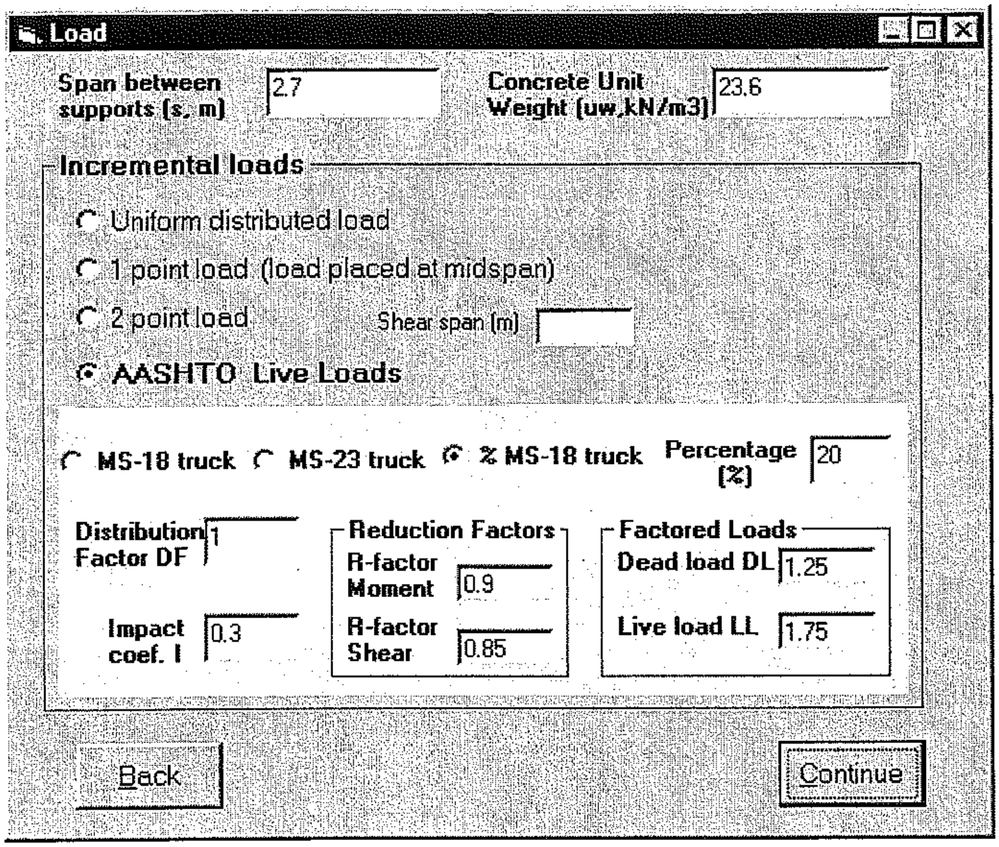
Figure 2. Load configurations.



For the AASHTO load (set as default), the user selects among MS-18 truck, MS-23 truck or a percentage of the MS-18 truck (enter value of percentage). User should enter a distribution factor based on wheel load distribution (DF), impact coefficient (I), dead load (DF) and live load (LL) factors.

Lane loading is also considered checked when the option AASHTO load is checked.

Default values of the above variables are indicated on the screen display below.



3.3.1.2 Section properties

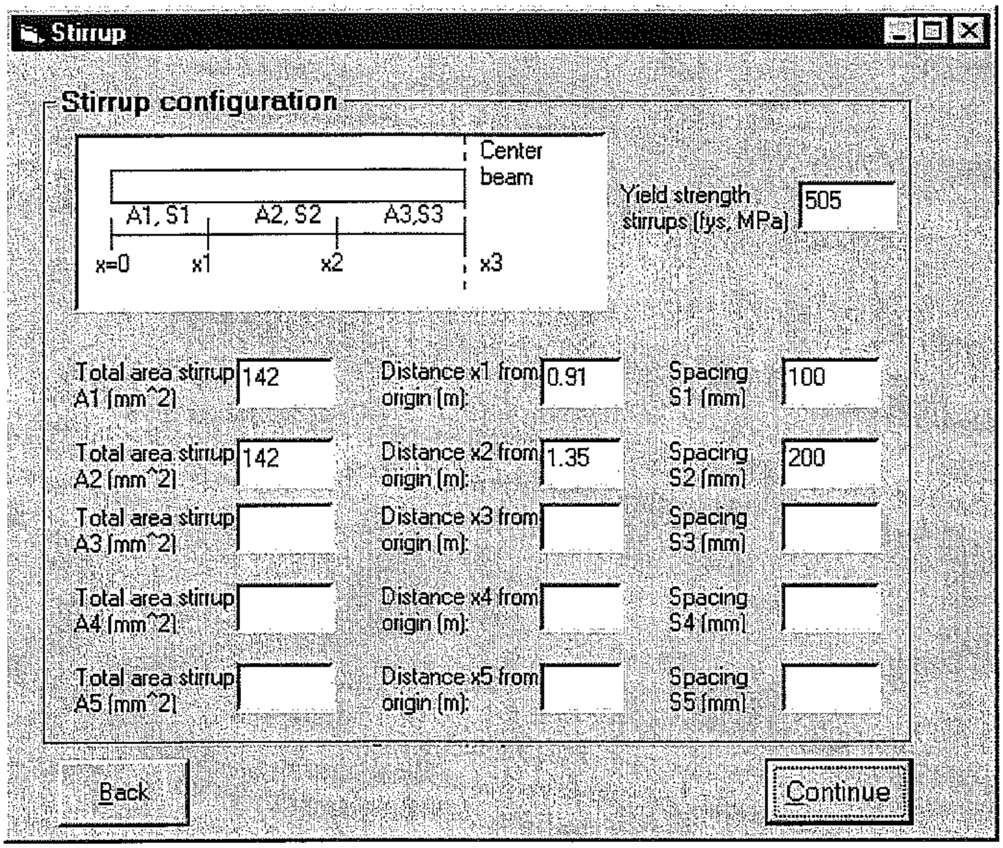
See Section properties under option Moment-curvature.

3.3.1.3 Material properties

See Material properties under option Moment-curvature.

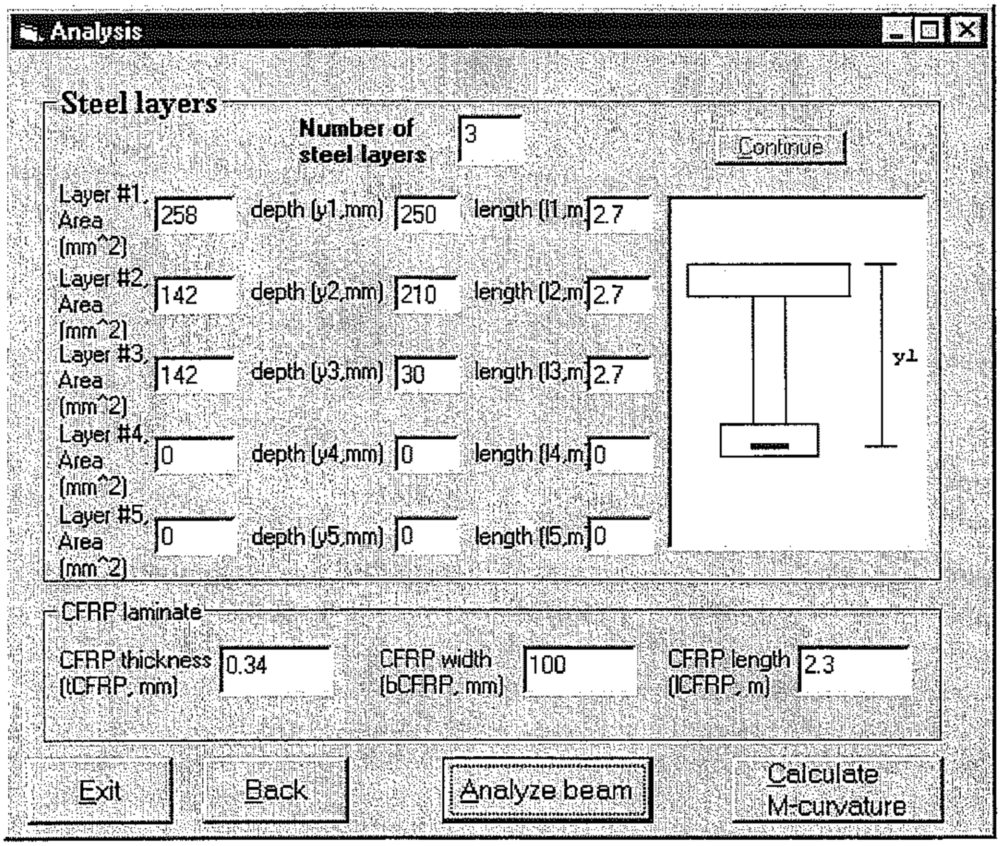
3.3.1.4 Stirrup configuration

Up to five different types of stirrups over half the beam span can be entered in this window. The stirrup configuration is assumed to be symmetric respect to the center of the beam. For every type of stirrup, the user should enter the total area of the stirrups (Ai), the spacing (Si), and the end location of this type of stirrup (xi). The stirrup specified at xi is considered to be over a distance $l_{stirrup}$ where $x(i-1) < l_{stirrup} \le xi$. All the stirrups are assumed to have the same yield strength (fys), the user should enter this value. If the beam being analyzed doesn't have stirrups, set the area of stirrups (Ai) equal to zero.



3.3.1.5 Steel and CFRP laminate configurations

See Steel and CFRP laminate configurations under the option Moment-Curvature.



3.3.2 Calculations

Section analysis is done at every 0.05 of the span length. The computer program internally generates a moment-curvature curve of the particular section. It also records particular moment values such as: moment at cracking of the concrete in tension; moment at yield of the steel longitudinal reinforcement; moment at crushing of concrete in top compression layer; maximum moment, moment at rupture of the CFRP laminate, whether it occurs before or after the moment at crushing of concrete; moment at steel rupture; and moment when the interfacial stresses between the CFRP laminate and concrete exceed the value of the shear strength of concrete (taken as 0.17 $\sqrt{f'c}$ in MPa by default).

If the option AASHTO loads was selected in the load windows, all the preceding values of moment are reduced moments (reduced by the corresponding reduction factor). For this option the computer also calculates unfactored maximum moment and shear values (Mexternal, Vexternal) under external live load at every 0.05 of the span length:

Mexternal (at distance x) = $(1+I) * DF * M_{lane} / 2$,

where M_{lane} is the maximum moment at x due to a single live loading lane (truck or lane loading, whichever governs).

Vexternal (at distance x) = $(1+I) * DF * V_{lane} / 2$, where V_{lane} is the maximum shear at x due to a single live loading lane (truck or lane loading, whichever governs).

In addition, the factored total moment (Mu) and shear (Vu) from dead load (self weight) and live load (AASHTO loads) are also calculated.

If the option of incremental loads is selected in the load windows, all the shear and moment values calculated are unfactored. The computer program calculates the moment and shear values due to self-weight (M self weight, V self weight). Total moment values at particular conditions are also calculated as indicated in the first paragraph of this section.

3.3.3 Output data: AASHTO loads

The table of results window shows the results from the beam analysis. At every 0.05 of the span length, the following information is provided: Maximum moment and shear values (Mexternal, Vexternal) calculated from the external live load (AASHTO truck or lane loading, whichever controls) as well as total factored moment and shear values (Mu, Vu). If the absolute maximum moment value for the entire beam does not fall at the midspan, the location and maximum moment value is substituted for the nearest 0.05 point output. In addition, the following reduced moment values are presented: maximum internal moment (Mmax); shear capacity of the section (Vmax); cracking moment (Mcracking); moment at steel yield (Msteelyield); moment when rupture of CFRP laminate occurs before (MCFRP rupt. 1) or after (MCFRP rupt. 2) compression concrete failure (M Compression); moment at compression concrete crushing (M Compression); moment at steel rupture (M steel rupture); and moment when interfacial stresses are higher than the shear stress of concrete (Minterfacial). This table of results is included in the output file.

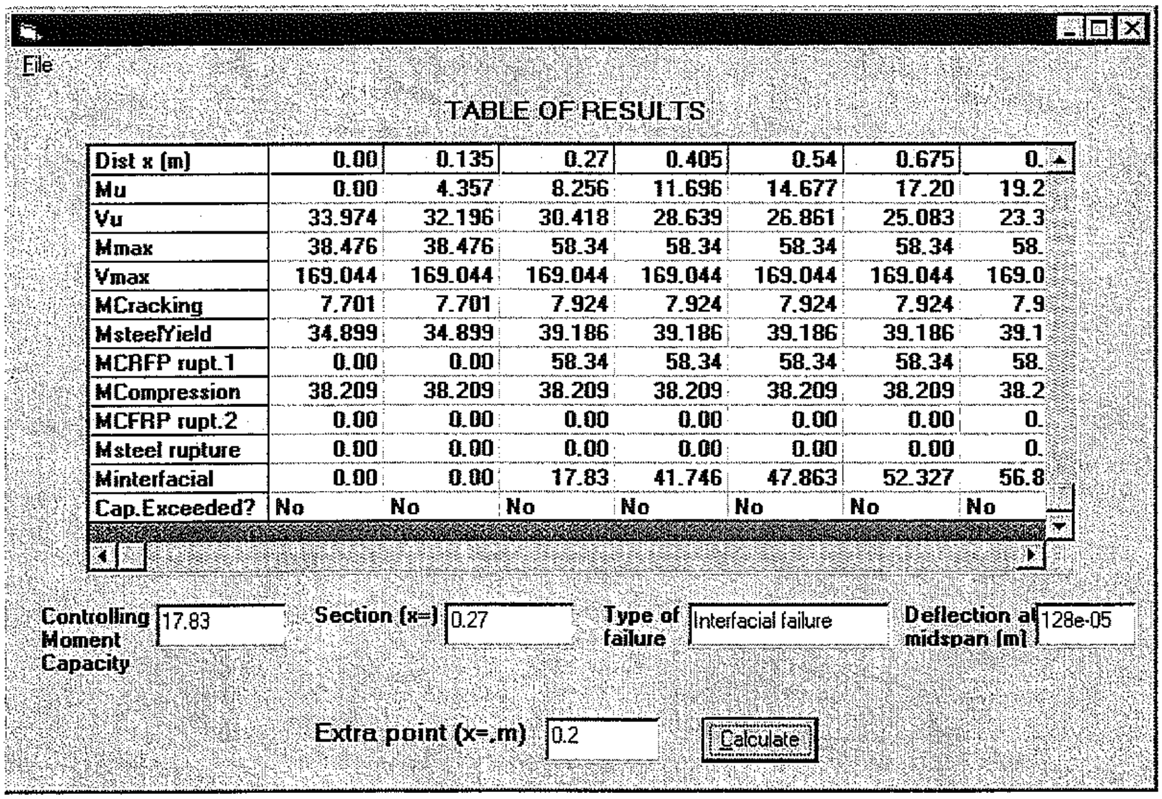
When the moment or shear capacity of the beam are exceeded by either the factored total moment or shear, the last row of the table of results will indicate: No (not exceeded), moment (moment capacity exceeded), shear (shear capacity exceeded), M&S (moment and shear capacities exceeded).

The controlling moment capacity value, which corresponds to the minimum value of moment capacity among all the sections considered when any type of failure occurs, is presented below the table of results. The corresponding distance of this critical section from the support and type of failure are also indicated. The value of deflection at midspan under service loads is also presented in this window.

The option **Extra point** allows the user to find the corresponding values for a section at a particular distance x from the support ($0 < x \leq s/2$). The user should input the value of the distance and click the button **Calculate**. Calculated values will be placed in column 12 of the table of results.

Under the **File** menu, the user can choose to **Save Results** (input data is included) or **Exit** the program. Exiting the program DOES NOT automatically save results.

As an output file the user obtains a summary of the input data and output data. The table of results is included, as well as the deflection at the midspan; and the location, value and type of failure for the critical section. For the section corresponding to the largest value of total factored moment (Mu), strains in the top compression layer, as well as total the force in the concrete; strains and forces at the CFRP and strains and stresses at every layer of longitudinal steel are also included.



Dist x (m)	0.00	0.135	0.27	0.405	0.54	0.675	0.
Mu	0.00	4.357	8.256	11.696	14.677	17.20	19.2
Vu	33.974	32.196	30.418	28.639	26.861	25.083	23.3
Mmax	38.476	38.476	58.34	58.34	58.34	58.34	58.
Vmax	169.044	169.044	169.044	169.044	169.044	169.044	169.0
MCracking	7.701	7.701	7.924	7.924	7.924	7.924	7.9
MsteelYield	34.899	34.899	39.186	39.186	39.186	39.186	39.1
MCRFP rupt.1	0.00	0.00	58.34	58.34	58.34	58.34	58.
MCompression	38.209	38.209	38.209	38.209	38.209	38.209	38.2
MCFRP rupt.2	0.00	0.00	0.00	0.00	0.00	0.00	0.
Msteel rupture	0.00	0.00	0.00	0.00	0.00	0.00	0.
Minterfacial	0.00	0.00	17.83	41.746	47.863	52.327	56.8
Cap.Exceeded?	No	No	No	No	No	No	No

3.3.4 Output data: Incremental Loads

A similar table of results window as the one presented in the option AASHTO loads shows the results from the beam analysis, see section 3.3.3.

At every section the computer calculates the smallest total shear and moment values that will lead to failure (M critical, V critical). The computer program also calculates the smallest value of external load (in addition to self-weight) either uniform load or point load that leads to any type of failure at any section considered. This value appears as a controlling load (Controlling Load) on the table of results window. The critical section is considered as the section where failure occurs under this value of external load. Its corresponding distance from the support and the type of failure originated are also presented on this window.

The value of deflection at midspan under critical load is also presented in this window

The option **Extra point** allows the user to find the corresponding values for a section at a particular distance x from the support ($0 < x \leq s/2$). The user should input the value of the distance and click the button **Calculate.** Calculated values will be placed in column 12 of the table of results.

Under the **File** menu, the user can choose to **Save Results** (input data is included) or **Exit** the program. Exiting the program DOES NOT automatically save results.

As an output file the user obtains a summary of the input data and output data. The table of results is included, as well as the deflection at the midspan; and the location, value and type of failure for the critical section. For the critical cross section, strains in the top compression layer, as well as total the force in the concrete; strains and forces at the CFRP and strains and stresses at every layer of longitudinal steel are also included.

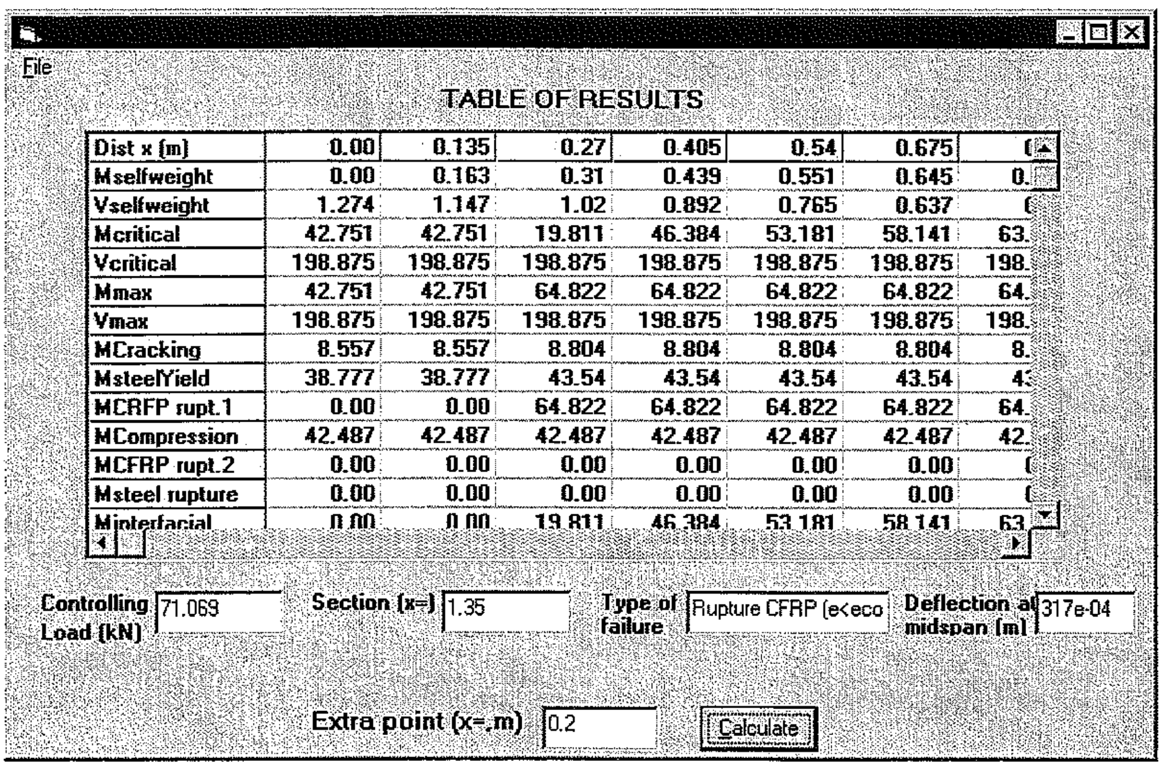


TABLE OF RESULTS

Dist x (m)	0.00	0.135	0.27	0.405	0.54	0.675	(
Mselfweight	0.00	0.163	0.31	0.439	0.551	0.645	0.
Vselfweight	1.274	1.147	1.02	0.892	0.765	0.637	(
Mcritical	42.751	42.751	19.811	46.384	53.181	58.141	63.
Vcritical	198.875	198.875	198.875	198.875	198.875	198.875	198.
Mmax	42.751	42.751	64.822	64.822	64.822	64.822	64.
Vmax	198.875	198.875	198.875	198.875	198.875	198.875	198.
MCracking	8.557	8.557	8.804	8.804	8.804	8.804	8.
MsteelYield	38.777	38.777	43.54	43.54	43.54	43.54	4:
MCRFP rupt.1	0.00	0.00	64.822	64.822	64.822	64.822	64.
MCompression	42.487	42.487	42.487	42.487	42.487	42.487	42.
MCFRP rupt.2	0.00	0.00	0.00	0.00	0.00	0.00	(
Msteel rupture	0.00	0.00	0.00	0.00	0.00	0.00	(
Minterfacial	0.00	0.00	19.811	46.384	53.181	58.141	63

4 REFERENCES

[1] Hognestad E., Hanson, N.W., and McHenry, D., "Concrete Stress Distribution in Ultimate Strength Design," ACI Journal, proc. Vol. 57, No. 2, February 1961.

[2] Antoine Naaman, Maria del Mar Lopez et al. Project "Repair and Strengthening of Reinforced Concrete Beams using CFRP Laminates", Final Report. MDOT Research project No. RC-1372. May, 1999.

Volume1: Summary Report. Report No. UMCEE 99-04. 23 pp.
Volume2: literature Review. Report No. UMCEE 97-12. 78 pp.
Volume 3: Behavior of Beams Strengthened for Bending. Report No. UMCEE 98-21. 58 pp.
Volume 4: Behavior of Beams Strengthened for Shear. Report No. UMCEE 98-38. 38 pp.
Volume 5: Behavior of Beams under Cyclic Loading at Low Temp. Report No. UMCEE 98-39. 42 pp.
Volume 6: Behavior of Beams Subjected to Freeze-Thaw Cycles. Report No. UMCEE 98-32. 68 pp.
Volume 7: Technical specifications. Report No. UMCEE 98-36. 28 pp.

[3] MacGregor J. G., "Reinforced Concrete. Mechanics and Design" Second Edition. Chapter 4: Flexure. Pages 73-125. Prentice Hall. 1988.

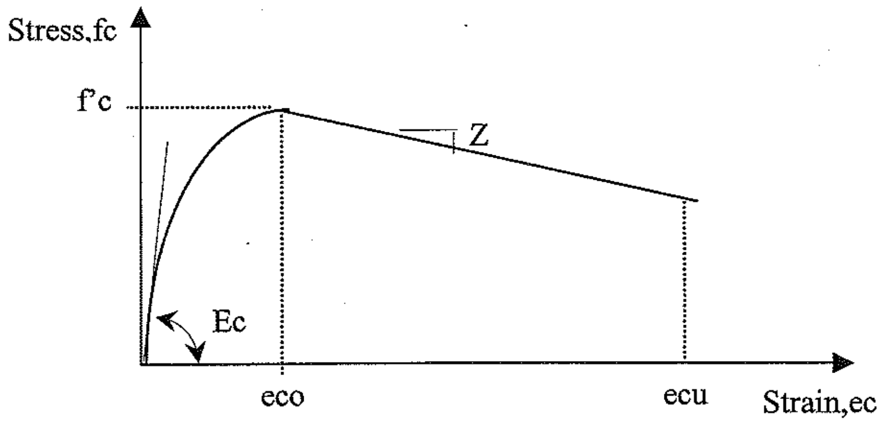
[4] MacGregor J. G., "Reinforced Concrete. Mechanics and Design" Second Edition. Chapter 3: Materials. Pages 54-55. Prentice Hall. 1988.

[5] Mattock A.H., Kriz L.B., and Hognestad E. "Rectangular Concrete Stress Distribution in Ultimate Strength Design." ACI Journal, Proceedings, Vol. 57, No. 8, February 1961, pp. 875-926.

[6] Bruneau M., Uang Ch-M. and Whittaker A., "Design of Steel Structures". Pages 8-9. Mac Graw-Hill. 1998

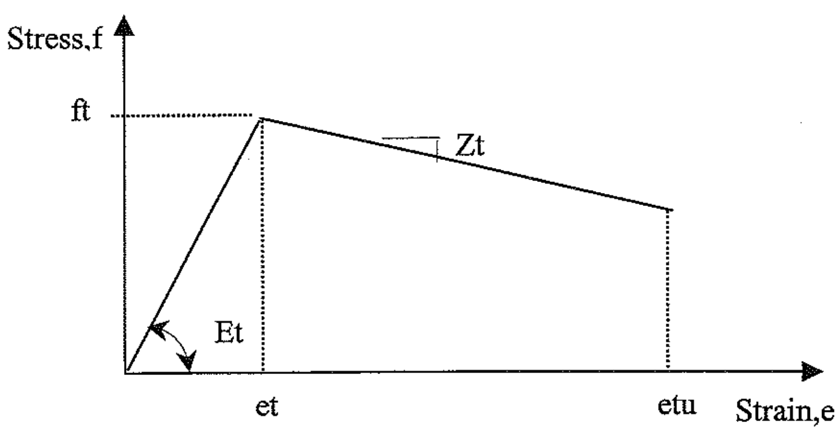
5 APPENDIX A

Hognestad's parabola: Analytical model of the compression behavior of concrete.



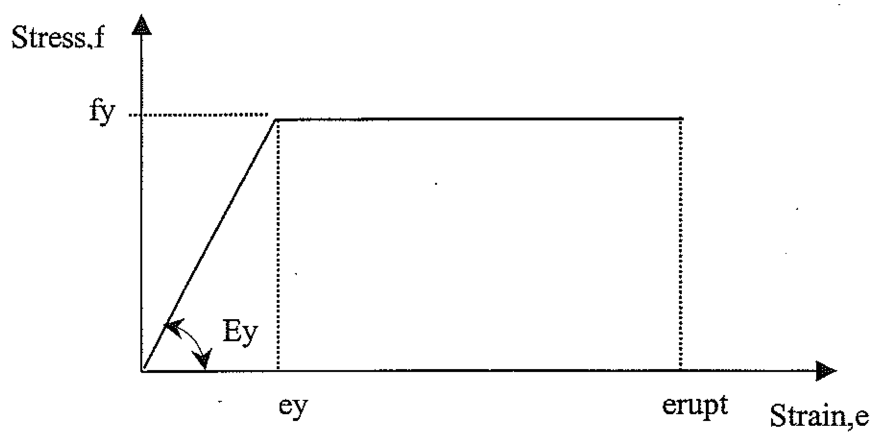
$0 \le ec \le eco$	$fc = f'c\,[\,2\,(ec/eco) - (ec/eco)^2]$
$eco \le ec$	$fc = f'c[1 - Z\,(ec - eco)]$

Tensile model of concrete



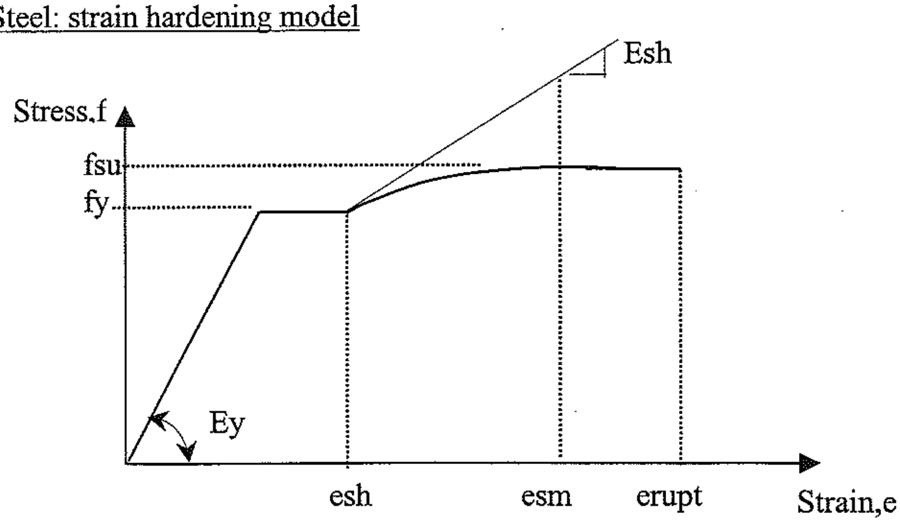
$e \le et$	$f = Et\,(e);$	where $et = ft/Et$
$e > et$	$f = ft\,[1 - Zt\,(e - et)]$	

Steel: linear elastic-perfectly plastic model



$e \leq ey$	$f = Ey\,(e)$;	where $ey = fy/Ey$
$e > ey$	$f = fy$	
$e > erupt$	$f = 0$	

Steel: strain hardening model



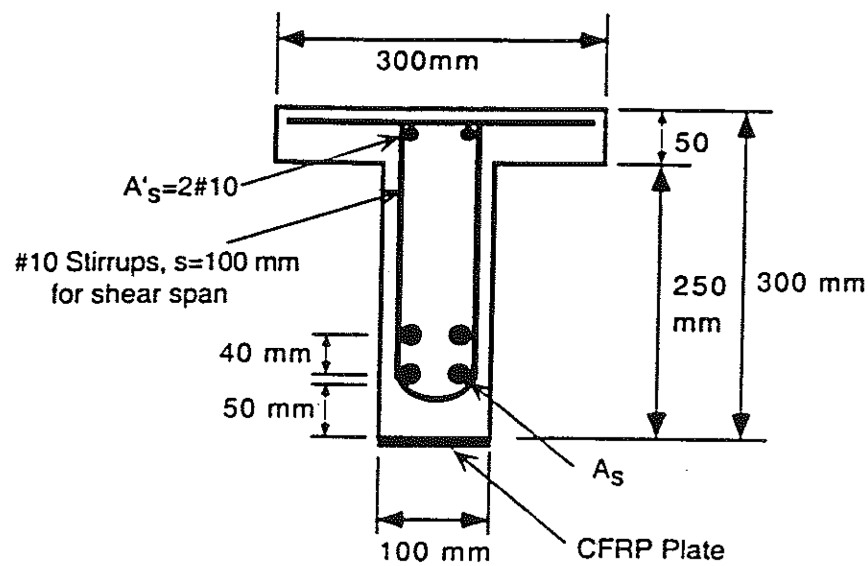
$e \leq ey$	$f = Ey\,(e)$	
$ey \leq e \leq esh$	$f = fy$;	define: $esm = esh + 2\,(fsu-fy)/Esh$
$esh \leq e \leq esm$	$fs = fy + (fsu-fy)\,[2\,\xi - \xi^2]$,	$\xi = (e-esh)/(esm-esh)$
$esm \leq e \leq erupt$	$f = fsu$	
$e > erupt$	$f = 0$	

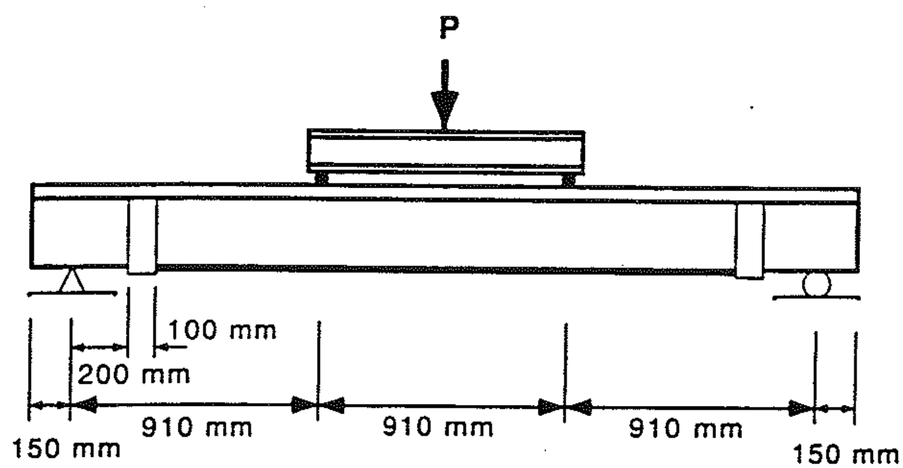
6 APPENDIX B. EXAMPLE

All the windows presented in the user manual are part of the same example. They correspond to the program input for the worked example. It was based on the reinforced concrete beams that were used in the bending test of the project "Repair and Strengthening of Reinforced Concrete Beams using CFRP Laminates", Final Report. MDOT Research Project No. RC-1372. May 1999 [2]. Comparison of results will be made with experimental data. For more reference, see Volume 3: Behavior of Beams Strengthened for Bending.

<u>Beam Configuration</u>

Beam # 3. As=400 mm^2, 2#10, 2#13
2 layers Tonen sheet (total thickness=0.34 mm, width=100 mm)
span between supports = 2.7 m, length CFRP plate = 2.3 m

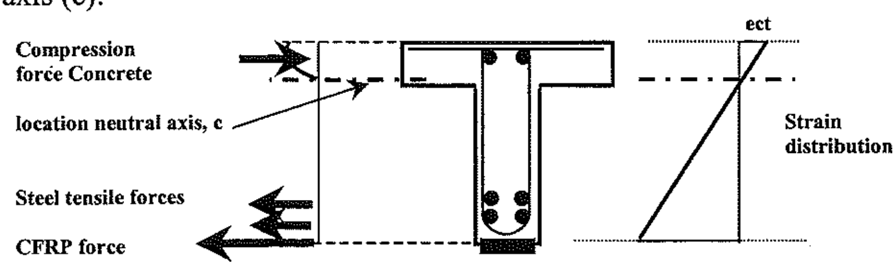




Worked Example

To calculate the moment capacity of a particular section of the selected strengthened beam, a complete moment-curvature should be generated. Every set of points of the moment-curvature is found through an iterative process, where strain compatibility and equilibrium of the section should be satisfied. Hand calculations would make this process too inefficient that is why the use of a computer program is needed.

As a worked example, one pair of moment-curvature points will be calculated. The iterative process will be overcome by using the computer program results for the location of the neutral axis (c).



Forces and strains acting on a cross section of the strengthened beam

Calculation of Maximum Moment.

Input data will be the same as the one used to produce the output of the moment-curvature option. Input is reproduced below for convenience:

INPUT DATA

SECTION PROPERTIES

Height (mm)=	300
Width web(mm)=	100
Width top flange(mm)=	300
Height top flange (mm)=	50
Height bottom flange(mm)=	0
Width bottom flange (mm)=	0
Transf. Moment of Inertia (mm^4)=	3.785713E+08
Centroid transformed section, ybr (mm)	186.2347

MATERIAL PROPERTIES

CONCRETE MODEL

Peak Compression strength (MPa)=	55.2
top compression strain	0.003
Peak Compression strain	0.003
Slope descending branch	150
Max compression strain	0.006
Modulus of Elasticity (MPa)=	35142.34

STEEL MODEL			
Yield strength (MPa)		455	
Modulus of elasticity (MPa)		200000	
CFRP MODEL			
CFRP ultimate strength (MPa)		3480	
CFRP modulus of Elasticity (MPa)		228000	

STEEL CONFIGURATION		Layers of steel	3
layer= 1			
Area steel (mm^2)	258		
distance from top (mm)	250		
layer= 2			
Area steel (mm^2)	142		
distance from top (mm)	210		
layer= 3			
Area steel (mm^2)	142		
distance from top (mm)	30		

CFRP CONFIGURATION	
CFRP width (mm)	100
CFRP thickness(mm)	0.34

For each one of the 80 points analyzed, the concrete compression strain is defined as follows:
First point (i=0): concrete top compression strain (ect_o) = ft / Et * (h - ybr) / ybr, where ft is the tensile strength of concrete (ft = 0.62$\sqrt{f'c}$, MPa), Et is the elastic modulus in tension of concrete (Et = Ec), h is the depth of the section, and ybr is the distance from the bottom fiber to the centroid of the transformed section.

For $1 \leq i \leq 40$, concrete top compression strain (ect_i) = (epsilon + increment1)
For $41 \leq i \leq 80$, concrete top compression strain (ect_i) = (epsilon + increment2),
where increment1 = (eco - ect_o)/40, eco is the peak compression strain
increment2 = (ecu – eco)/40, ecu is the maximum compression strain
and epsilon is the value of the concrete top compression strain (ect) of the preceding (i-1) point. To calculate the maximum moment, it corresponds to point #21, out of 80 (highlighted for convenience from the output of the moment-curvature option):

increment1=(-0.003-(-8.007183E-05))/40 = -7.2998E-05
ect = (-1.467038E-03-7.2998E-05) = -1.540036E-03

<u>Location of neutral axis:</u>
<u>First Iteration:</u>

Location of the neutral axis (c, mm) = h/2 = 300/2 = 150 mm.
Assign c1=0, c2=h=300

Strain distribution:
Concrete top compression strain (ect)= 1.540036E-03

Strain steel layer #1 (depth d1 = 250 mm) = -(c – d1) / c * ect
= -(150-250)/150*1.540036E-03
= 1.0267E-03

Strain steel layer #2 (depth d2 = 210 mm) = -(c – d2) / c * ect
= -(150-210)/150*1.540036E-03
= 6.1601E-04

Strains steel layer #3 (depth d3 = 30 mm) = -(c – d3) / c * ect
= -(150-30)/150*1.540036E-03
= -1.232E-03

Strain CFRP (depth dCFRP = 300 mm) = -(c – dCFRP) / c * ect
= -(150-300)/150*1.540036E-03
= 1.540E-03

Stress distribution:
Concrete top compression stress (from Hognestad's parabola, see Appendix A) =
Peak Compression strength (MPa)= 55.2
Top compression strain (eco) = 0.003, therefore ect<eco then
$fc = f'c\ [\ 2\ (ec/eco) - (ec/eco)^2]$
fc = 55.2 [2 (1.540036E-03/0.003)- (1.540036E-03/0.003)^2]
fc = 42.1268 MPa
The tensile properties for concrete are not considered for this example.

The steel is modeled to be elastic-perfectly plastic (no strain hardening), see Appendix A.
ey = fy/Ey = 455/200000 = 0.002275

Stress steel layer #1 = Ey (e)
= 200000 (1.0267E-03)
= 205.34 MPa

Stress steel layer #2 = Ey (e)
= 200000 (6.1601E-04)
= 123.202 MPa

Stress steel layer #3 = Ey (e)
= 200000 (-1.232E-03)
= -246.4 MPa

Stress CFRP = Eu (e)
= 228000 (1.540E-03)
= 351.12 MPa

Equilibrium of forces:

Force concrete $(F = \int \text{stress*dArea}) = (-\int f'c\ [\ 2\ (ec/eco) - (ec/eco)^2]\ b\ dy),\ o < y \le c$
where ec = ect / c* y

solving this integral = -709.189 kN

Force steel layer #1 = stress * Area = 205.34 * 258 = 52.977 kN
Force steel layer #1 = stress * Area = 123.202 * 142 = 17.494 kN
Force steel layer #1 = stress * Area = -246.4 *142 = -34.99 kN
Force CFRP = stress * Area = 351.12 *34 = 11.938 kN
$\sum$ Forces = $\sum$ Forces compression + $\sum$ Forces in tension =0
–709.189 –34.99 + 52.977 +17.494 +11.938 = -744.179 + 82.409 = -661.77

If $\sum$ Forces <0, then c2=c = 150, and c(next iteration) = (c1+c2)/2 = (0+150)/2=75 mm

(in the case where $\sum$ Forces $\geq$ 0, then c1=c, and c(next iteration) = (c1+c2)/2)

This iterative process will be repeated until the value of $\sum$ Forces approaches zero.

Final Iteration:

Concrete top compression strain (ect) = 1.540036E-03, from Computer program
Location of the neutral axis (c, mm) = ect/curvature = 1.540036E-03 / 4.15546E-05
= 37.0605 mm

Strain distribution:
Concrete top compression strain (ect)= 1.540036E-03
Strain steel layer #1 (depth d1 = 250 mm) = -(c – d1) / c * ect
= -(37.0605-250)/37.0605*1.540036E-03
= 8.8486E-03
Strain steel layer #2 (depth d2 = 210 mm) = -(c – d2) / c * ect
= -(37.0605-210)/37.0605*1.540036E-03
= 7.1864E-03
Strains steel layer #3 (depth d3 = 30 mm) = -(c – d3) / c * ect
= -(37.0605-30)/37.0605*1.540036E-03
= -2.9340E-04
Strain CFRP (depth dCFRP = 300 mm) = -(c – dCFRP) / c * ect
= -(37.0605-300)/37.0605*1.540036E-03
= 1.0926E-02

Stress distribution:
Concrete top compression stress (from Hognestad's parabola, see Appendix A) =
Peak Compression strength (MPa)= 55.2
Top compression strain (eco) = 0.003, therefore ect<eco then
fc = f'c [2 (ec/eco) - (ec/eco)^2]
fc = 55.2 [2 (1.540036E-03/0.003)- (1.540036E-03/0.003)^2]
fc = 42.1268 MPa
The tensile properties for concrete are not considered for this example.

The steel is modeled to be elastic-perfectly plastic (no strain hardening), see Appendix A.
ey = fy/Ey = 455/200000 = 0.002275
Stress steel layer #1 = fy,. e>ey

= 455 MPa

Stress steel layer #2 = fy, e>ey

= 455 MPa

Stress steel layer #3 = Ey (e)

= 200000 (-2.9340E-04)

= -58.68 MPa

Stress CFRP = Eu (e)

= 228000 (1.0926E-02)

= 2491.13 MPa

Equilibrium of forces:

Force concrete ($F = \int$ stress*dArea) $= (-\int f'c\ [\ 2\ (ec/eco) - (ec/eco)^2]\ btf\ dy),\ o < y \le c$
where ec = ect / c* y, btf = 300 mm width top flange

solving this integral = - 261.240 kN
centroid of this volume, depth from top = 13 mm

Force steel layer #1 = stress * Area = 455 * 258 = 117.39 kN
Force steel layer #1 = stress * Area = 455 * 142 = 64.610 kN
Force steel layer #1 = stress * Area = -58.68*142 = -8.332 kN
Force CFRP = stress * Area = 2491.13 *34 = 84.70 kN
$\sum$ Forces compression = $\sum$ Forces in tension
-261.24 –8.332 = 117.39+64.61+84.7
-269.6 = 266.7 (difference 1%, O.K. for hand calculation)

Internal Moment:

Internal Moment, (**Mmax**) = $\sum$force * distance
= (-261.24*13 –8.332*30 +117.39*250 +64.610*210 +84.7*300)
= **64.7 kN-m**

2 examples of output files are presented below.
Sign convention used in the computer program: (+) indicates tensile strain/stress/force;
(-) indicates compression strain/stress/force.

Moment-Curvature Option.

CFRP COMPUTER PROGRAM
Moment-Curvature analysis

INPUT DATA

SECTION PROPERTIES

Height (mm)=	300
Width web(mm)=	100
Width top flange(mm)=	300
Height top flange (mm)=	50
Height bottom flange(mm)=	0
Width bottom flange (mm)=	0
Transf. Moment of Inertia (mm^4)=	3.785713E+08
Centroid transformed section, ybr (mm)	186.2347

MATERIAL PROPERTIES
CONCRETE MODEL

Peak Compression strength (MPa)=	55.2
top compression strain	0.003
Peak Compression strain	0.003
Slope descending branch	150
Max compression strain	0.006
Modulus of Elasticity (MPa)=	35142.34

STEEL MODEL

Yield strength (MPa)	455
Modulus of elasticity (MPa)	200000

CFRP MODEL

CFRP ultimate strength (MPa)	3480
CFRP modulus of Elasticity (MPa)	228000

STEEL CONFIGURATION
Layers of steel 3

layer= 1

Area steel (mm^2)	258
distance from top (mm)	250

layer= 2

Area steel (mm^2)	142
distance from top (mm)	210

layer= 3

Area steel (mm^2)	142
distance from top (mm)	30

CFRP CONFIGURATION

CFRP width (mm)	100
CFRP thickness(mm)	0.34

OUTPUT FILE

Maximum moment (kN-m)	**64.8065**
curvature at Mmax (1/mm)	4.15546E-05
Moment at ultimate (kN-m)	41.4422
curvature at Mult (1/mm)	6.186319E-05

INTERNAL MOMENT (kN-m)	CURVATURE (1/mm)
9.210782	6.569996E-07
9.859742	2.511919E-06
14.80925	3.936971E-06
19.81538	5.316737E-06
24.84542	6.684109E-06
29.65922	7.995515E-06
34.68854	9.356164E-06
39.26682	1.061833E-05
43.77975	1.205665E-05
46.46199	1.382317E-05
48.55297	1.607549E-05
50.01746	1.837897E-05
51.73738	2.091871E-05
53.29188	2.333878E-05
54.9712	2.594244E-05
56.61081	2.854676E-05
58.16601	3.098173E-05
59.81471	3.365041E-05
61.59145	3.646224E-05
63.16074	3.896879E-05
64.8065	**4.15546E-05**
41.4422	6.186319E-05
41.48043	6.653169E-05
41.53968	7.063716E-05
41.65294	7.534128E-05
41.68747	8.027769E-05
41.77024	8.492655E-05
41.82426	8.918252E-05
41.86385	9.415578E-05
41.92072	9.867319E-05

41.98571	1.033111E-04
42.0585	1.080743E-04
42.09196	1.121995E-04
42.12947	1.163813E-04
42.19708	1.21038E-04
42.25607	1.266784E-04
42.29929	1.311111E-04
42.34632	1.356072E-04
42.37103	1.396655E-04
42.3978	1.43753E-04
42.45449	1.484058E-04
42.48655	1.526691E-04
42.52077	1.569635E-04
42.52673	1.607007E-04
42.59544	1.656471E-04
42.60431	1.694118E-04
42.61411	1.731765E-04
42.62451	1.769412E-04
42.66923	1.813727E-04
42.68144	1.851513E-04
42.69426	1.889299E-04
42.70871	1.927086E-04
42.72379	1.964871E-04
42.70284	1.995295E-04
42.71836	2.032942E-04
42.73437	2.070589E-04
42.75089	2.108236E-04
42.72955	2.138022E-04
42.74783	2.175531E-04
42.72751	2.204964E-04
42.74627	2.242336E-04
42.72552	2.271418E-04
42.74373	2.308655E-04
42.7131	2.337391E-04
42.70149	2.374493E-04
42.69028	2.411594E-04
42.67947	2.448695E-04
42.67047	2.485797E-04
42.66211	2.522898E-04
42.65402	0.000256
42.64622	2.597101E-04
42.6387	2.634202E-04
42.59272	2.652086E-04
42.5855	2.68892E-04
42.57858	2.725755E-04
42.57195	2.762589E-04

42.52716	2.779428E-04
42.5209	2.815999E-04
42.51493	2.85257E-04
42.47422	2.868651E-04
42.47041	2.904963E-04

strain concrete top	Force Concrete (kN)
-8.007183E-05	-4.336195
-1.5307E-04	-37.55153
-2.260683E-04	-61.26772
-2.990665E-04	-83.29806
-3.720646E-04	-104.4288
-4.450628E-04	-124.8388
-5.18061E-04	-145.2
-5.910593E-04	-165.1337
-6.640575E-04	-183.7887
-7.370557E-04	-196.3498
-8.10054E-04	-202.9518
-8.830522E-04	-209.4279
-9.560504E-04	-213.1983
-1.029049E-03	-218.9507
-1.102047E-03	-224.091
-1.175045E-03	-230.0293
-1.248043E-03	-235.5214
-1.321041E-03	-241.9003
-1.39404E-03	-247.294
-1.467038E-03	-252.9996
-1.540036E-03	**-257.8929**
-1.613034E-03	-187.9685
-1.686033E-03	-190.9321
-1.759031E-03	-193.1383
-1.832029E-03	-193.2294
-1.905027E-03	-196.2844
-1.978026E-03	-197.368
-2.051024E-03	-199.4222
-2.124022E-03	-202.2452
-2.19702E-03	-204.0972
-2.270018E-03	-205.5671
-2.343017E-03	-206.6748
-2.416015E-03	-209.0878
-2.489013E-03	-211.2596
-2.562011E-03	-212.2764
-2.63501E-03	-214.2355
-2.708008E-03	-216.0514
-2.781006E-03	-217.6483
-2.854004E-03	-219.8813

-2.927002E-03	-221.9462
-3.000001E-03	-222.944
-0.003075	-224.5465
-0.00315	-225.9952
-0.003225	-228.2575
-0.0033	-228.4467
-3.375001E-03	-230.2752
-3.450001E-03	-231.8608
-3.525001E-03	-233.3624
-3.600001E-03	-233.7552
-3.675001E-03	-235.0792
-3.750001E-03	-236.3197
-3.825001E-03	-237.2183
-3.900001E-03	-238.0314
-3.975001E-03	-239.8454
-4.050001E-03	-240.5528
-4.125001E-03	-241.2027
-4.200001E-03	-241.795
-4.275001E-03	-243.4063
-4.350001E-03	-243.6756
-0.004425	-244.9375
-0.0045	-245.0998
-0.004575	-246.2932
-0.00465	-246.3858
-0.004725	-247.5056
-0.0048	-247.5266
-0.004875	-247.5089
-0.00495	-247.4524
-5.024999E-03	-247.1815
-5.099999E-03	-246.8421
-5.174999E-03	-246.4791
-5.249999E-03	-246.0924
-5.324999E-03	-245.6822
-5.399999E-03	-247.3482
-5.474999E-03	-246.8983
-5.549998E-03	-246.4243
-5.624998E-03	-245.926
-5.699998E-03	-247.458
-5.774998E-03	-246.9154
-5.849998E-03	-246.348
-5.924998E-03	-247.479
-5.999998E-03	-246.6925

strain CFRP	Force CFRP (kN)
1.170281E-04	0.9072015
6.005055E-04	4.655118

9.55023E-04	7.403338
1.295955E-03	10.04624
1.633168E-03	12.66032
1.953592E-03	15.14424
2.288788E-03	17.74269
2.594439E-03	20.11209
2.952936E-03	22.89116
3.409895E-03	26.43351
4.012593E-03	31.10562
4.630639E-03	35.89672
5.319563E-03	41.23725
5.972584E-03	46.29947
6.680684E-03	51.78866
7.388984E-03	57.27941
8.046475E-03	62.37628
8.774081E-03	68.01668
9.544631E-03	73.98998
0.0102236	79.25334
1.092634E-02	**84.70101**
1.694592E-02	0
1.827347E-02	0
1.943212E-02	0
2.077035E-02	0
2.217828E-02	0
2.349994E-02	0
2.470373E-02	0
2.612271E-02	0
2.740494E-02	0
0.0287233	0
3.007927E-02	0
3.124384E-02	0
3.242536E-02	0
0.0337494	0
3.536851E-02	0
3.662533E-02	0
3.790114E-02	0
3.904564E-02	0
4.019891E-02	0
4.152175E-02	0
4.272573E-02	0
4.393905E-02	0
4.498522E-02	0
4.639412E-02	0
4.744854E-02	0
4.850295E-02	0
4.955737E-02	0

5.081182E-02	0
0.0518704	0
5.292898E-02	0
5.398756E-02	0
5.504614E-02	0
5.588384E-02	0
5.693825E-02	0
5.799266E-02	0
5.904707E-02	0
5.986567E-02	0
6.091594E-02	0
6.172391E-02	0
6.277008E-02	0
6.356755E-02	0
6.460964E-02	0
6.539674E-02	0
6.643478E-02	0
6.747282E-02	0
6.851087E-02	0
0.0695489	0
7.058695E-02	0
7.162499E-02	0
7.266303E-02	0
7.370108E-02	0
7.416257E-02	0
7.519261E-02	0
7.622264E-02	0
7.725268E-02	0
7.768283E-02	0
7.870498E-02	0
7.972711E-02	0
8.013454E-02	0
0.0811489	0

layer # 1

strain steel	stress steel (MPa)
8.417808E-05	16.83562
4.749096E-04	94.98193
7.581745E-04	151.6349
1.030118E-03	206.0235
1.298963E-03	259.7925
1.553816E-03	310.7632
1.82098E-03	364.196
2.063523E-03	412.7046
2.350104E-03	455
2.718737E-03	455

3.208818E-03	455
3.711691E-03	455
4.273627E-03	455
4.805645E-03	455
5.383562E-03	455
5.961646E-03	455
6.497389E-03	455
7.091561E-03	455
7.72152E-03	455
8.27516E-03	455
8.848614E-03	**455**
1.385276E-02	455
1.494689E-02	455
1.590026E-02	455
1.700329E-02	455
0.0181644	455
1.925361E-02	455
2.024461E-02	455
2.141492E-02	455
2.247128E-02	455
2.355775E-02	455
2.467555E-02	455
2.563386E-02	455
0.0266063	455
0.0276975	455
2.903459E-02	455
3.006977E-02	455
3.112078E-02	455
3.206237E-02	455
3.301125E-02	455
3.410146E-02	455
3.509228E-02	455
3.609088E-02	455
3.695019E-02	455
3.811177E-02	455
3.897795E-02	455
3.984413E-02	455
0.0407103	455
4.174319E-02	455
4.261284E-02	455
4.348249E-02	455
4.435214E-02	455
4.522179E-02	455
4.590737E-02	455
4.677354E-02	455
4.763972E-02	455

4.850589E-02	455
4.917556E-02	455
5.003829E-02	455
5.069909E-02	455
0.0515584	455
5.221046E-02	455
5.306637E-02	455
5.370978E-02	455
5.456232E-02	455
5.541485E-02	455
5.626738E-02	455
5.711992E-02	455
5.797245E-02	455
5.882499E-02	455
5.967753E-02	455
6.053006E-02	455
6.090214E-02	455
6.174801E-02	455
6.259387E-02	455
6.343973E-02	455
6.378569E-02	455
6.462498E-02	455
6.546427E-02	455
6.579129E-02	455
6.662409E-02	455

layer # 2

strain steel	stress steel (MPa)
5.789809E-05	11.57962
3.744329E-04	74.88657
6.006957E-04	120.1391
8.174483E-04	163.4897
1.031598E-03	206.3196
1.233995E-03	246.7991
1.446733E-03	289.3467
1.63879E-03	327.7579
1.867838E-03	373.5677
2.16581E-03	433.162
2.565799E-03	455
2.976532E-03	455
3.436879E-03	455
3.872094E-03	455
4.345865E-03	455
4.819775E-03	455
5.25812E-03	455
5.745545E-03	455
6.263031E-03	455

6.716408E-03	455
7.18643E-03	**455**
1.137824E-02	455
1.228562E-02	455
1.307477E-02	455
1.398964E-02	455
1.495329E-02	455
1.585655E-02	455
1.667731E-02	455
1.764869E-02	455
1.852435E-02	455
0.0194253	455
2.035258E-02	455
2.114588E-02	455
2.195105E-02	455
2.285598E-02	455
2.396745E-02	455
2.482533E-02	455
0.0256965	455
2.647575E-02	455
2.726113E-02	455
2.816522E-02	455
2.898551E-02	455
2.981234E-02	455
3.052216E-02	455
3.148589E-02	455
3.220148E-02	455
3.291706E-02	455
3.363265E-02	455
3.448828E-02	455
3.520678E-02	455
3.592529E-02	455
3.664379E-02	455
0.0373623	455
3.792619E-02	455
3.864177E-02	455
3.935736E-02	455
4.007295E-02	455
4.062347E-02	455
4.133616E-02	455
4.187924E-02	455
4.258905E-02	455
4.312478E-02	455
4.383175E-02	455
4.436022E-02	455
4.506435E-02	455

4.576847E-02	455
4.647261E-02	455
4.717673E-02	455
4.788086E-02	455
4.858499E-02	455
4.928912E-02	455
4.999325E-02	455
0.0502938	455
5.099232E-02	455
5.169085E-02	455
5.238937E-02	455
5.266798E-02	455
5.336098E-02	455
5.405398E-02	455
5.431668E-02	455
5.500424E-02	455
layer # 3	
strain steel	stress steel (MPa)
-6.036184E-05	-12.07237
-7.771248E-05	-15.5425
-1.079591E-04	-21.59183
-1.395643E-04	-27.91287
-1.715414E-04	-34.30828
-2.051974E-04	-41.03948
-2.373761E-04	-47.47522
-2.725094E-04	-54.50189
-3.023581E-04	-60.47162
-3.223606E-04	-64.47213
-3.277893E-04	-65.55785
-3.31683E-04	-66.33661
-3.284891E-04	-65.69782
-3.288853E-04	-65.77706
-3.237737E-04	-64.75475
-3.186421E-04	-63.72842
-3.185914E-04	-63.71828
-3.115292E-04	-62.30584
-3.001725E-04	-60.03451
-2.979742E-04	-59.59485
-2.933982E-04	**-58.67964**
2.428614E-04	48.57227
3.099181E-04	61.98363
3.60084E-04	72.01679
4.282092E-04	85.64184
5.033035E-04	100.6607
5.697709E-04	113.9542
6.244518E-04	124.8904

7.006514E-04	140.1303
7.631754E-04	152.6351
8.293134E-04	165.8627
8.992118E-04	179.8424
9.499705E-04	189.9941
1.002425E-03	200.4849
1.06913E-03	213.826
1.165342E-03	233.0685
1.225326E-03	245.0651
1.287209E-03	257.4417
1.33596E-03	267.1921
1.385588E-03	277.1176
1.452174E-03	290.4348
1.505073E-03	301.0146
1.558905E-03	311.781
1.596022E-03	319.2044
1.669412E-03	333.8824
1.707353E-03	341.4706
1.745294E-03	349.0589
1.783236E-03	356.6471
1.841181E-03	368.2363
1.879539E-03	375.9078
1.917897E-03	383.5794
1.956255E-03	391.251
1.994613E-03	398.9226
2.010883E-03	402.1766
2.048824E-03	409.7648
2.086765E-03	417.353
2.124706E-03	424.9413
2.139066E-03	427.8133
2.176594E-03	435.3188
2.189891E-03	437.9781
2.227007E-03	445.4015
2.239255E-03	447.8509
2.275964E-03	455
2.287174E-03	455
2.323478E-03	455
2.359782E-03	455
2.396087E-03	455
2.432391E-03	455
2.468695E-03	455
0.002505	455
2.541304E-03	455
2.577608E-03	455
2.556258E-03	455
2.591762E-03	455

2.627265E-03	455
2.662769E-03	455
2.638285E-03	455
2.672999E-03	455
2.707713E-03	455
2.680956E-03	455
2.714893E-03	455

Beam-Analysis Option
AASHTO loads

CFRP COMPUTER PROGRAM
Beam analysis

INPUT DATA

SECTION PROPERTIES

Height (mm)=	300
Width web(mm)=	100
Width top flange(mm)=	300
Height top flange (mm)=	50
Height bottom flange(mm)=	0
Width bottom flange (mm)=	0
Transf. Moment of Inertia (mm^4)=	3.753864E+08
Centroid transformed section, ybr (mm)	185.6206

MATERIAL PROPERTIES
CONCRETE MODEL

Peak Compression strength (MPa)=	55.2
top compression strain	0.003
Peak Compression strain	0.003
Slope descending branch	150
Max compression strain	0.006
Modulus of Elasticity (MPa)=	37719.7

STEEL MODEL

Yield strength (MPa)	455
Modulus of elasticity (MPa)	200000

CFRP MODEL

CFRP ultimate strength (MPa)	3480
CFRP modulus of Elasticity (MPa)	228000

STEEL STIRRUP MODEL

Stirrup steel yield strength(MPa)	505

STEEL CONFIGURATION

Layers of steel 3

layer= 1

Area steel (mm^2)	258
distance from top (mm)	250
Length layer (m)	2.7

layer= 2	
Area steel (mm^2)	142
distance from top (mm)	210
Length layer (m)	2.7

layer= 3	
Area steel (mm^2)	142
distance from top (mm)	30
Length layer (m)	2.7

Area stirrups (mm^2)	142
Distance from x origin (m)	0.91
Spacing (mm)	100
Area stirrups (mm^2)	142
Distance from x origin (m)	1.35
Spacing (mm)	200
Area stirrups (mm^2)	0
Distance from x origin (m)	0
Spacing (mm)	0
Area stirrups (mm^2)	0
Distance from x origin (m)	0
Spacing (mm)	0
Area stirrups (mm^2)	0
Distance from x origin (m)	0
Spacing (mm)	0

CFRP CONFIGURATION	
CFRP width (mm)	100
CFRP thickness(mm)	0.34
CFRP length(m)	2.3

LOAD CONFIGURATION	
Span (m)	2.7
Concrete Unit weight (kN/m^3)	23.6
AASHTO Load	
%MS-18 truck	20
Load	
Coefficient distribution	1
Coefficient impact	0.3
Coefficient dead load	1.25
Coefficient live load	1.75
Moment Reduction Coefficient	0.9
Shear Reduction Coefficient	0.85

OUTPUT FILE
Moments in kN-m, shear in KN

Controlling Moment 17.82985
Distance x(m)= 0.27
Failure mode Interfacial failure

Deflection (m) 1.280249E-03

Results Table

section x= 0 0.135 0.27 0.405 0.54 0.675 0.8100001
0.9450001 1.08 1.215 1.35 1.35
Mexternal 0 2.373097 4.496394 6.369892 7.99359 9.367489
10.49159 11.36589 11.99038 12.36508 12.48998 12.48998
Vexternal 18.50368 17.5785 16.65331 15.72813 14.80294 13.87776
12.95257 12.02739 11.10221 10.17702 9.251841 9.251841
Mu 0 4.357223 8.255789 11.6957 14.67696 17.19956
19.26351 20.8688 22.01544 22.70342 22.93275 22.93275
Vu 33.97444 32.19607 30.41769 28.63932 26.86095 25.08258
23.3042 21.52584 19.74746 17.96909 16.19072 16.19072
Mmax 38.47626 38.47626 58.33987 58.33987 58.33987 58.33987
58.33987 58.33987 58.33987 58.33987 58.33987 58.33987
Vmax 169.0435 169.0435 169.0435 169.0435 169.0435 169.0435
169.0435 97.17937 97.17937 97.17937 97.17937 97.17937
MCrack 7.701107 7.701107 7.92399 7.92399 7.92399 7.92399
7.92399 7.92399 7.92399 7.92399 7.92399 7.92399
MYield 34.8989 34.8989 39.18592 39.18592 39.18592 39.18592
39.18592 39.18592 39.18592 39.18592 39.18592 39.18592
MCRFP1 0 0 58.33987 58.33987 58.33987 58.33987
58.33987 58.33987 58.33987 58.33987 58.33987 58.33987
MComp. 38.20904 38.20904 38.20904 38.20904 38.20904 38.20904
38.20904 38.20904 38.20904 38.20904 38.20904 38.20904
MCFRP2 0 0 0 0 0 0 0 0
0 0 0 0
Msteel rupt. 0 0 0 0 0 0 0 0
0 0 0 0
Minterfac1 0 0 17.82985 41.74556 47.86274 52.32693
56.81833 56.81833 56.81833 56.81833 56.81833 56.81833
Exceeded Capacity? No No No No No No
No No No No No No