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# TEACHING STRUCTURAL STEEL DESIGN USING MATHCAD PROGRAM

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## ABSTRACT

This paper demonstrates the integration of Mathcad programming in a steel design course at the University of Qatar. It discusses the advantages of Mathcad programming over other programming formats and provides guidelines to incorporate Mathcad programming into the steel design course. A Mathcad program for the analysis and design of steel beams is presented to show the attractive computational environment of Mathcad. The importance of Mathcad programming in teaching steel design courses is also illustrated. Successful integration of Mathcad programming as a teaching and learning tool in the steel design course resulted in an increased students' understanding of structural analysis and design.

**KEY WORDS:** Mathcad, Learning Tool, Teaching Tool, Structural Steel Design, High-Level Programming.

## INTRODUCTION

Computers have become indispensable analysis and design tools for engineers because they are capable of producing massive amounts of visual data. A large number of commercial computer programs are currently available to solve engineering problems. This situation led computer users to forget that they have to be always familiar with the theory and assumptions behind these programs. This problem is especially significant for undergraduate engineering students who probably do not completely understand the theory.

One solution to this problem consists of having students write their own analysis and design programs using a high-level programming language such as FORTRAN or C++. This approach is not desirable for two reasons. The effort required on the part of the students would exceed the benefit they might achieve relative to the course objectives. Also, the level of programming expertise of students at the undergraduate level is not adequate.

A better solution consists of having students write their own analysis and design programs using a commercial software platform such as Mathcad [1], which is an efficient learning environment for technical topics such as engineering design. The computational and presentation capabilities of Mathcad allow for the solution of mathematically based problems and for the effective communication of both problem and solution. It contains powerful presentation capabilities, which include the use of charts, graphic objects, and animation effects. It can also easily import objects from other application programs, such as images and digital photographs. These capabilities offer significant learning enhancements to engineering students. Mathcad makes possible new learning strategies for students and instructors. What-if discussions, trend analyses, trial and error analyses, and optimization are all valuable learning activities. Taking advantage of the computational power and speed of Mathcad, instructors and students can quickly cycle through design problem scenarios. It allows students to apply the solution logic without the programming difficulties and overhead associated with high-level language programming. Mathcad has proven to be an excellent teaching and learning tool for reinforced concrete design[2].

The proposed paper describes the integration of Mathcad programming in a steel design course. It discusses advantages of Mathcad programming and provides recommendations for incorporating Mathcad programming in the steel design course. A Mathcad program for the analysis and design of steel beams is presented to show the attractive computational environment of Mathcad. The importance of Mathcad programming in teaching steel design courses is also illustrated.

## COURSE DESCRIPTION

Structural Steel Design is an introductory steel design course, which is required for civil engineering students specializing in structures. There are three lecture hours per week and one weekly two-hour tutorial session. The course uses the American Institute of Steel Construction Load and Resistance Factor Design (LRFD) methodology throughout [3]. Six distinct blocks or topics are covered within the course including structural systems, tension members, compression members, flexural members, beam-columns, and connections. During the semester, the students must complete an engineering design project involving the design of a simple structural system.

## ADVANTAGES OF MATHCAD PROGRAMMING

Because it eliminates much of the programming overhead, Mathcad is superior to high-level languages. Mathcad is relatively easy to learn and straightforward and at the same time offers powerful tools to create sophisticated programs. More accomplished students can make advanced Mathcad programs while less experienced students can still write a simple Mathcad program that gets the job done.

Mathcad programming logic closely resembles the logical flow of the engineering thought process. In Mathcad, the equations used to represent the engineering thought process look the same as they are written in a reference book. Once the equations are entered into the program, it is easy to check the validity of the logic because the calculations are immediate. As a result, there is an obvious relationship between the engineering thought process, the equations needed to represent that thought process, and the iteration through those equations to achieve an optimal solution.

In Mathcad program, different formatting, including various fonts, colors, patterns, and borders can be used to improve the readability of the text. By using different drawing entities and varying their color, pattern, and line weight attributes, highly readable drawings are produced to illustrate the computations.

Mathcad program provides outstanding graphics capabilities. The way in which Mathcad tend to relate numbers to graphics is important. Since Mathcad can generate graphs from a range of numerical values, it is easy to generate a graphical depiction of a solution. Furthermore, it is possible to directly alter the graphical output by changing the desired parameters. Like spreadsheets, as soon as a change is made in the input data, the results are updated and the plots are redrawn. Other types of charts, such as pie and histogram charts, can also be easily generated. The Mathcad program allows for the determination of an optimum design simply by changing the input data and observing the changes in the design.

## GENERAL GUIDELINES FOR INCORPORATING MATHCAD

The computer usage in undergraduate courses aims at helping students to learn the actual course objectives. Therefore, the effort required to learn the software package should not eclipse the student's effort devoted to learning the course objectives.

When using Mathcad students should start by outlining their solution thought process using a complete hand solution. This is important for two reasons. First, it ensures that students work through the theory. Second, it improves their chances of entering the correct equations into the program. Students needs to generate some type of graphic output from their Mathcad program. This is important because it causes them to visualize the effect of their decisions. Students should be reminded that the computer program is a merely a tool. They must always evaluate the computer output. They should use Mathcad program for the exploration of alternate problem scenarios, observation of trends, and expansion of the discussion to related topics. The time spent using the program to explore problem scenarios can lead students to a better understanding of the concepts involved in the problems.

## MATHCAD PROGRAM FOR STRUCTURAL STEEL ANALYSIS AND DESIGN

The key to incorporate Mathcad in the steel design course is to constantly reinforce the notion that it is the engineer not the computer who must eventually solve the problem. The computer is merely a tool.

A Mathcad program, which has been incorporated into a steel design course, is discussed. The program, which is concerned with the design of structural steel beams, was written to automate the manual design procedure [4-7]. The Mathcad program consists of the following computational steps:

**STEP 1.**
The first step consists of reading the required beam input data (Figure 1).

**STEP 2.**
The second step involves the determination of the ultimate bending moment $M_u$ (Figure 2). The number and positions of the concentrated (point) loads are not fixed in order to create a generic program.

**STEP 3.**
The third step involves the determination of the beam moment gradient $C_b$ (Figure 3).

**STEP 4.**
The fourth step consists of computing the design bending moment $M_n$ (Figure 4).

**STEP 5.**
The fifth step consists of displaying the analysis results and drawing the beam bending moment diagram (Figure 5).

## ILLUSTRATIVE EXAMPLE

This example is presented to demonstrate the analysis and design features of the Mathcad program. The example consists of the design of a simply-supported structural steel beam with a span of 30 ft. The beam is subjected to a uniform dead load of 0.31 kip/ft and to a uniform live load of 1.0 kip/ft. The objective of the design is to select the lightest (i.e., most economical) W-shape that resists these loads. The first W-shape considered (W10*77) was selected using the Zx table of the LRFD Book. The input data and output results for the first design trial is summarized in Figure 6. The results show that the first design is not economical (i.e., Mn >> Mu).

The program is easily used to improve the first design trial by selecting a smaller and lighter W-shape. In the second trial, the shape W10*49 is selected. The input data and output results for the section design trial are summarized in Figure 7. Since the design strength of the section is less than the ultimate moment (i.e., $M_n < M_u$), the selected shape is not adequate. In the third design trial, the W12*58 is selected. The input data and output results for the third design trial is summarized in Figure 8. The results show that an optimum design was easily reached after only two trials. This shows the efficiency of the Mathcad program presented.

# STEEL BEAM DESIGN USING LRFD METHOD

## STEP 1. READ INPUT DATA

**Read material properties data**

| | | | | | | |
|---|---|---|---|---|---|---|
| $Fy \equiv 50$ | ksi | $Fr \equiv 10$ | ksi | | | Yield and residual strength |
| $E \equiv 29000$ | ksi | $G \equiv 11200$ | ksi | | | Elastic and shear modulus |

**Read section properties data**

| | | | | | | |
|---|---|---|---|---|---|---|
| $h \equiv 14.0$ | in | $A \equiv 26.5$ | $in^2$ | $ow \equiv 0.09$ | $\frac{kips}{ft}$ | Beam height, area, and own weight |
| $Bf \equiv 14.520$ | in | $Tf \equiv 0.710$ | in | | | Flange width and thickness |
| $Ix \equiv 999$ | $in^4$ | $Sx \equiv 143$ | $in^3$ | $Zx \equiv 157$ | $in^3$ | Moment of inertia, section modulus, and plastic modulus (about x-axis) |
| $Iy \equiv 362$ | $in^4$ | $J \equiv 4.06$ | $in^4$ | $Cw \equiv 16000$ | $in^3$ | Moment of inertia (about y-axis , torsional constant, and warping constant |

**Read geometry data**

| | | | | |
|---|---|---|---|---|
| $L \equiv 40$ | ft | | | Beam span |
| $Lb \equiv 40$ | ft | | | Braced length |
| $Lb1 \equiv 0$ | ft | $Lb2 \equiv 40$ | ft | Beam lateral bracing positions (left and right) |

**Read load data**

| | | | | |
|---|---|---|---|---|
| $M1 \equiv 0$ | ft kips | $M2 \equiv 0$ | ft kips | Left and right- end moments |
| $DL \equiv 0.31$ | $\frac{kips}{ft}$ | $LL \equiv 1.0$ | $\frac{kips}{ft}$ | Beam uniform dead and live loads |
| $NCL \equiv 1$ | | | | Number of concentrated loads |

AA := READPRN ( "test.dat" )

$P := AA^{<1>}$ $\quad$ $l := AA^{<0>}$

**Fig.1. Step 1 of Mathcad program**

## STEP 2. DETERMINATION OF ULTIMATE BENDING MOMENT Mu

**Compute the beam reaction R1 due to the uniform load (w), the concentrated loads ($_K P$), and the end-moments (M1 & M2)**

$$w := 1.2\cdot(DL + ow) + 1.6\cdot LL$$

$$k := 0..\ NCL$$

$$R1 := \frac{w\cdot L}{2} + \left[\sum_{k=0}^{NCL-1}\left[\frac{P_k\cdot\left(L - l_k\right)}{L}\right]\right]$$

$$R1 := R1 - \frac{M1 + M2}{L}$$

**Compute the beam ultimate bending moment Mu**

$$i := 0..\ L \qquad j := 0..\ 0$$

$$x_i := i$$

$$xx_{i,j} := \begin{vmatrix} x_i - l_j & \text{if } x_i - l_j \geq 0 \\ 0 & \text{otherwise} \end{vmatrix}$$

$$M_i := M1 + R1\cdot x_i - \sum_{j=0}^{NCL-1} P_j\cdot xx_{i,j} - \frac{w\cdot\left(x_i\right)^2}{2}$$

$$Mu := \max(M)$$

**Fig.2. Step 2 of Mathcad program**

## STEP 3. DETERMINATION OF MOMENT GRADIENT Cb

**Compute the maximum bending moment (Mmax) in the braced length (Lb3)**

$Lb3 := Lb2 - Lb1$

$k := 0 .. Lb3 \qquad j := 0 .. 0$

$y_k := k + Lb1$

$$xx_{k,j} := \begin{cases} y_k - l_j & \text{if } y_k - l_j \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

$$MX_k := M1 + R1 \cdot y_k - \sum_{j=0}^{NCL-1} P_j \cdot xx_{k,j} - \frac{w \cdot (x_k)^2}{2}$$

$Mmax := \max(MX)$

**Compute the bending moment MA, MB, and MC**

$k := 0 .. 2 \qquad j := 0 .. 0$

$$y_k := Lb1 + (k+1) \cdot \frac{(Lb2 - Lb1)}{4}$$

$$xx_{k,j} := \begin{cases} y_k - l_j & \text{if } x_k - l_j \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

$$MY_k := M1 + R1 \cdot y_k - \sum_{j=0}^{NCL-1} P_j \cdot MX_{i,ji} - \frac{w \cdot (y_k)^2}{2}$$

$MA := MY_0 \qquad MB := MY_1 \qquad MC := MY_2$

**Compute the beam moment gradient Cb**

$$Cb := \frac{12.5 \cdot Mmax}{2.5 \cdot Mmax + 3 \cdot MA + 4 \cdot MB + 3 \cdot MC}$$

**Fig. 3. Step 3 of Mathcad program**

## STEP 4. COMPUTE BEAM DESIGN STRENGTH (Φ Mn)

**Check flange local buckling (i.e., check if the section is compact)**

$\lambda := \frac{Bf}{2 \cdot Tf}$ $\lambda p := \frac{65}{\sqrt{Fy}}$ $\lambda r := \frac{141}{\sqrt{Fy - 10}}$

$$FLB := \begin{cases} 0 & \text{if } \lambda < \lambda p \\ 1 & \text{if } \lambda p < \lambda \le \lambda r \\ 2 & \text{if } \lambda p > \lambda r \end{cases}$$

Shape is compact
Shape is noncompact
Shape is slender

**Check lateral torsional buckling**

$$Ry := \sqrt{\frac{Iy}{A}}$$

$$X1 := \frac{\pi \cdot \sqrt{\frac{E \cdot G \cdot J \cdot A}{2}}}{Sx} \qquad X2 := 4 \cdot \frac{Cw \cdot \left(\frac{Sx}{G \cdot J}\right)^2}{Iy}$$

$$Lp := 300 \cdot \frac{Ry}{12 \cdot \sqrt{Fy}} \qquad Lr := \frac{Ry \cdot X1 \cdot \sqrt{1 + \sqrt{1 + X2 \cdot (Fy - Fr)^2}}}{12 \cdot (Fy - Fr)}$$

$$LTB := \begin{cases} 0 & \text{if } Lb \le Lp \\ 1 & \text{if } Lp < Lb \le Lr \\ 2 & \text{if } Lb > Lr \end{cases}$$

No risk of lateral torsional buckling
Risk of inelastic lateral torsional buckling
Risk of elastic lateral torsional buckling

**Compute plastic moment (Mp)**

$$Mp := \begin{cases} \frac{Fy \cdot Zx}{12} & \text{if } \left(\frac{Zx}{Sx}\right) \le 1.5 \\ \frac{(1.5 \cdot Fy \cdot Sx)}{12} & \text{if } \left(\frac{Zx}{Sx}\right) > 1.5 \end{cases}$$

Plastic moment

$$\phi Mp := 0.9 \cdot Mp$$

$$Mr := \frac{(Fy - Fr) \cdot Sx}{12}$$

Moment corresponding to first yield

**Fig. 4. Step 4 of Mathcad program**

$$Mn1 := Cb \cdot \left[ Mp - (Mp - Mr) \cdot \frac{(Lb - Lp)}{(Lr - Lp)} \right]$$

$$Mn2 := \begin{vmatrix} Mn1 & \text{if } Mn1 \le Mp \\ Mp & \text{otherwise} \end{vmatrix}$$

Nominal strength $M_n$ (compact + inelastic torsional buckling)

$$Mcr := \frac{Cb \cdot Sx \cdot X1 \cdot \sqrt{2} \cdot \sqrt{1 + \frac{X1^2 \cdot X2}{2 \cdot \left( \frac{12 \cdot Lb}{Ry} \right)^2}}}{12 \cdot \frac{12 \cdot Lb}{Ry}}$$

$$Mn3 := \begin{vmatrix} Mcr & \text{if } Mcr \le Mp \\ Mp & \text{otherwise} \end{vmatrix}$$

Nominal strength $M_n$ (compact + elastic torsional buckling)

$$Mn4 := \begin{vmatrix} Mp & \text{if } LTB = 0 \\ Mn2 & \text{if } LTB = 1 \\ Mn3 & \text{if } LTB = 2 \end{vmatrix}$$

Nominal strength $M_n$ for compact sections

$$Mn5 := \left[ Mp - (Mp - Mr) \cdot \frac{(\lambda - \lambda p)}{(\lambda r - \lambda p)} \right]$$

$$Mn6 := \begin{vmatrix} Mn4 & \text{if } Mn5 \ge Mn4 \\ Mn5 & \text{otherwise} \end{vmatrix}$$

Nominal strength $M_n$ for noncompact sections

$$\phi Mn := \begin{vmatrix} (0.9 \cdot Mn4) & \text{if } FLB = 0 \\ (0.9 \cdot Mn6) & \text{if } FLB = 1 \end{vmatrix}$$

Design strength $\phi M_n$

**Fig. 4. Step 4 of Mathcad program (continued)**

## STEP 5. OUTPUT RESULTS

| | | |
|---|---|---|
| Lb= 40 ft | Lp= 13.07 ft | Lr= 38.4 ft |
| λ = 10.23 | λp = 9.19 | λr = 22.29 |

| | | |
|---|---|---|
| ϕMp= 588.75 | ft kips | Plastic bending moment |
| Mu= 416 | ft kips | Ultimate bending mome |
| ϕMn= 462.02 | ft kips | Design bending moment |

**"The beam is adequate ϕMn >= Mu"**
**"The beam is not adequate ϕMn < Mu"**

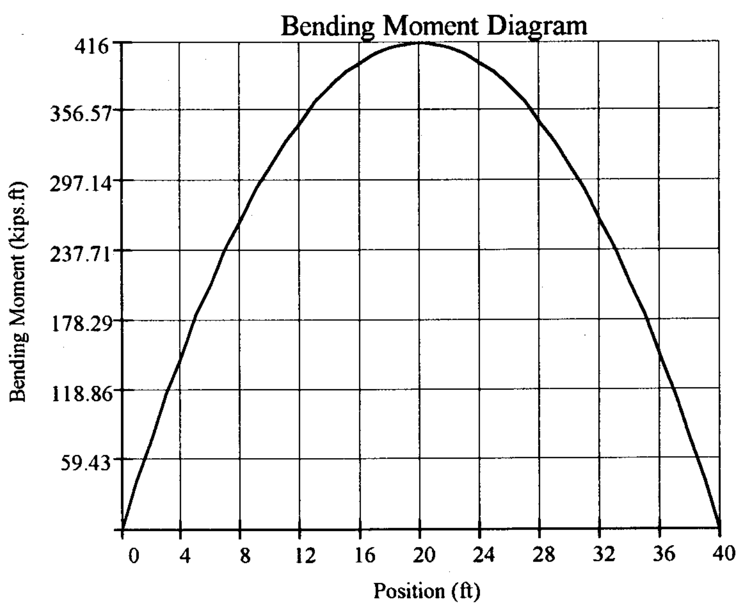


**Fig. 5. Step 5 of Mathcad program**

## INPUT DATA

**Material properties data**

| | | | | | | |
|---|---|---|---|---|---|---|
| Fy ≡50 | ksi | Fr ≡10 | ksi | | | Yield and residual strength |
| E≡29000 | ksi | G≡11200 | ksi | | | Elastic and shear modulus |

**Section properties data**

| | | | | | | |
|---|---|---|---|---|---|---|
| d ≡10.6 | in | A ≡22.6 | $in^2$ | ow ≡0.077 | $\frac{kips}{ft}$ | Beam height, area, and own weight |
| Bf ≡10.19 | in | Tf ≡0.870 | in | | | Flange width and thickness |
| Ix≡455 | $in^4$ | Sx≡85.9 | $in^3$ | Zx ≡97.6 | $in^3$ | Moment of inertia, section modulus, and plastic modulus (about x-axis) |
| Iy ≡154 | $in^4$ | J≡5.11 | $in^4$ | Cw ≡3630 | $in^6$ | Moment of inertia (about y-axis , torsional constant, and warping constant |

## OUTPUT RESULTS

| | | |
|---|---|---|
| Lb = 30 ft | Lp = 9.23 ft | Lr = 40.01 ft |
| $\lambda$ = 5.86 | $\lambda p$ = 9.19 | $\lambda r$ = 22.29 |

| | | |
|---|---|---|
| $\phi$ Mp = 366 | ft kips | Plastic bending moment |
| $\phi$ Mn = 332.86 | ft kips | Design bending moment |
| Mu = 232.25 | ft kips | Ultimate bending moment |

**"The beam is adequate if $\phi$ Mn >= Mu"**
**"The beam is not adequate if $\phi$ Mn < Mu"**

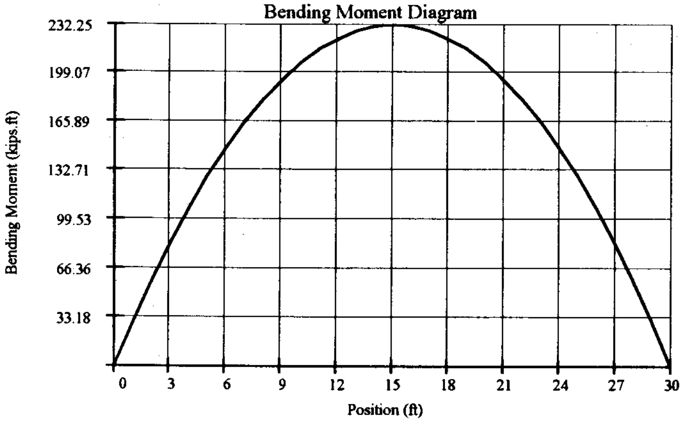


**Fig. 6. Input and output results for first design trial**

## INPUT DATA

**Material properties data**

| | | | | |
|---|---|---|---|---|
| Fy ≡50 | ksi | Fr ≡10 | ksi | Yield and residual strength |
| E ≡29000 | ksi | G ≡11200 | ksi | Elastic and shear modulus |

**Section properties data**

| | | | | | | |
|---|---|---|---|---|---|---|
| d ≡9.98 | in | A ≡14.4 | $in^2$ | ow ≡0.049 | $\frac{kips}{ft}$ | Beam height, area, and own weight |
| Bf ≡10.0 | in | Tf ≡0.560 | in | | | Flange width and thickness |
| Ix ≡272 | $in^4$ | Sx ≡54.6 | $in^3$ | Zx ≡60.4 | $in^3$ | Moment of inertia, section modulus, and plastic modulus (about x-axis) |
| Iy ≡93.4 | $in^4$ | J ≡1.39 | $in^4$ | Cw ≡2070 | $in^6$ | Moment of inertia (about y-axis , torsional constant, and warping constant |

## OUTPUT RESULTS

| | | |
|---|---|---|
| Lb = 30 ft | Lp = 9 ft | Lr = 28.37 ft |
| λ = 8.93 | λp = 9.19 | λr = 22.29 |

| | | |
|---|---|---|
| ϕ Mp = 226.5 | ft kips | Plastic bending moment |
| ϕ Mn = 173.71 | ft kips | Design bending moment |
| Mu = 228.47 | ft kips | Ultimate bending moment |

**"The beam is adequate if ϕ Mn >= Mu"**
**"The beam is not adequate if ϕ Mn < Mu"**

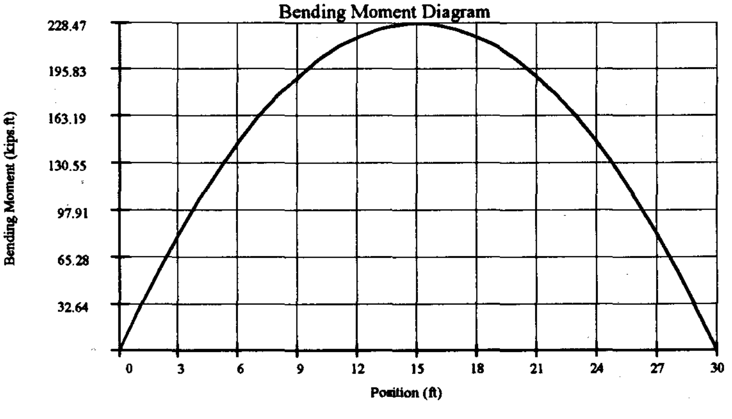


**Fig. 7. Input and output results for second design trial**

## INPUT DATA

**Material properties data**

| | | | | | | |
|---|---|---|---|---|---|---|
| Fy ≡50 | ksi | Fr ≡10 | ksi | | | Yield and residual strength |
| E ≡29000 | ksi | G ≡11200 | ksi | | | Elastic and shear modulus |

**Section properties data**

| | | | | | | |
|---|---|---|---|---|---|---|
| d ≡12.19 | in | A ≡17.0 | $in^2$ | ow ≡0.058 | $\frac{kips}{ft}$ | Beam height, area, and own weight |
| Bf ≡10.01 | in | Tf ≡0.640 | in | | | Flange width and thickness |
| Ix ≡475 | $in^4$ | Sx ≡78 | $in^3$ | Zx ≡86.4 | $in^3$ | Moment of inertia, section modulus, and plastic modulus (about x-axis) |
| Iy ≡107 | $in^4$ | J ≡2.10 | $in^4$ | Cw ≡3570 | $in^6$ | Moment of inertia (about y-axis , torsional constant, and warping constant |

## OUTPUT RESULTS

| | | | | | |
|---|---|---|---|---|---|
| Lb = 30 | ft | Lp = 8.87 | ft | Lr = 26.96 | ft |
| $\lambda$ = 7.82 | | $\lambda p$ = 9.19 | | $\lambda r$ = 22.29 | |
| $\phi$ Mp = 324 | | ft kips | | Plastic bending moment | |
| $\phi$ Mn = 232.17 | | ft kips | | Design bending moment | |
| Mu = 229.68 | | ft kips | | Ultimate bending moment | |

**"The beam is adequate if $\phi$ Mn >= Mu"**
**"The beam is not adequate if $\phi$ Mn < Mu"**

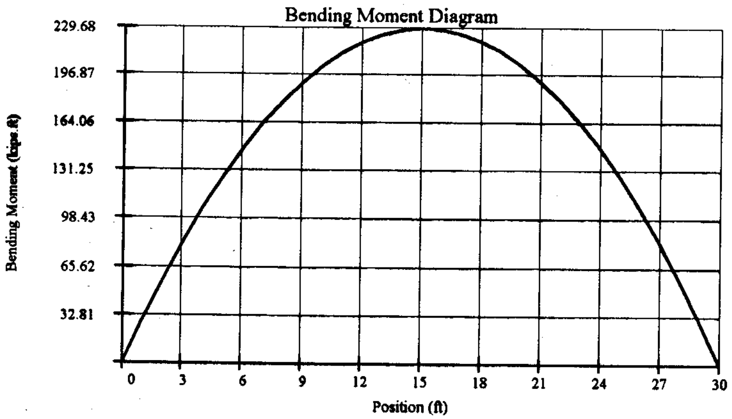


**Fig. 8. Input and output results for third design trial**

## CONCLUSIONS

Mathcad contains tools, which enhances and supplements student's understanding of the course material. The versatility, accessibility, and ease of use make Mathcad a platform for creating learning modules for technically based courses. Mathcad contains the capabilities for classroom computation with a greater degree of accuracy, reliability, and presentation quality. In addition, its speed at repetitive tasks, and its programmability, makes new learning strategies possible. Mathcad programs take time for students to develop, but with many benefits in return. They create opportunities for meaningful understanding of technical material. A well-designed Mathcad program can engage students to explore and discover the subject, drawing them deeper into the secrets that it holds.

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# APPENDIX

Some Conversion factors, between customary and SI metric unit, Useful in Structural Steel Design

| | To Convert | To | Multiply by |
|---|---|---|---|
| Forces | kip force | kN | 4.448 |
| | lb | N | 4.448 |
| | kN | kip | 0.225 |
| Stresses | ksi | MPa | 6.895 |
| | psi | MPa | 0.006985 |
| | MPa | ksi | 0.1450 |
| | MPa | psi | 145.0 |
| Moments | ft.kip | kN.m | 1.356 |
| | kN.m | ft.kip | 0.7376 |
| Uniform Loading | kip/ft | kN/m | 14.590 |
| | kN/m | kip/ft | 0.06852 |
| | kip/ft$^2$ | kN/m$^2$ | 47.88 |
| | psf | N/m$^2$ | 47.88 |
| | kN/m$^2$ | kip/ft$^2$ | 0.02089 |