T.C.

ISTANBUL KÜLTÜR UNIVERSITY

INSTITUTE OF GRADUATE STUDIES

A PROPOSED MODEL FOR ESTIMATING THE CURVATURE DUCTILITY OF REINFORCED CONCRETE SECTIONS

Master of Science Thesis

Mohamad MARI

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Department: Civil Engineering

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Supervisor: Prof. Dr. HÜSEYİN FARUK KARADOĞAN

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Preamble:

I would like to acknowledge and thank the following important people who have supported me, not only during the course of this project, but throughout my master's degree.

I would like to express my gratitude to my supervisor Prof. Dr. Farouk KARADĞAN for his unwavering support. Who expertly guided me and shared the excitement and enthusiasm to keep me constantly engaged with my thesis topic.

All my gratefulness to İstanbul Kültür University and all the academic staff of civil engineering department for letting me fulfil my dream to get the master's degree.

And finally, I would like to thank my family and all my close friends. And great thanks to my father who encourage me and believed in me. You have all helped me to focus on what has been a hugely rewarding and enriching process.

ABSTRACT

Reinforced concrete is a widely used system for constructing structures all over the world. Currently, the main requirement for designing reinforced concrete structures is achieving a ductile behavior by deforming before the section fracture under the ultimate limit state. In general, to ensure a ductile behavior, an adequate moment-curvature is important. Nowadays, one of the most used methods for quantifying the ductility of the section is through curvature ductility. Previously, several analytical models were proposed to determine this parameter and its effect. However, some problems are encountered due to the major assumptions in developing these models which reduce their reliability for general applications. In this study, computer software was developed to calculate the curvature ductility of reinforced concrete columns and walls. In addition to that, an enhanced mathematical model for estimating the curvature ductility is proposed. Finally, a parametric study was conducted to evaluate the influencing parameters on the curvature ductility of different sections. The results of this study have shown a significant improvement in the proposed against the currently available one. Furthermore, the developed program was capable of defining the moment-curvature with good accuracy in comparison to both ETABS and Xtract. Moreover, the results of the parametric study have presented a considerable independency of the sectional ductility on the level of the confinement and the tensile strength of the concrete used. This study is expected to help practicing engineers in their daily works by reliably estimating the behavior of reinforced concrete sections.

ÖZET

Betonarme, tüm dünyada yapıların inşasında yaygın olarak kullanılan bir sistemdir. Günümüzde, betonarme yapıların tasarımı için temel gereksinim, nihai sınır durumu altında kesit kırılmasından önce şekil değiştirerek sünek bir davranış elde etmektir. Genel olarak, sünek bir davranış sağlamak için yeterli bir moment eğriliği önemlidir. Günümüzde, kesitin sünekliğini ölçmek için en çok kullanılan yöntemlerden biri eğrilik sünekliğidir. Daha önce, bu parametreyi ve etkisini belirlemek için birkaç analitik model önerildi. Ancak, genel uygulamalar için güvenilirliğini azaltan bu modellerin geliştirilmesinde büyük varsayımlar nedeniyle bazı sorunlarla karşılaşılmaktadır. Bu çalışmada, betonarme kolon ve duvarların eğrilik sünekliğini hesaplamak için bilgisayar yazılımı geliştirilmiştir. Buna ek olarak, eğrilik sünekliğini tahmin etmek için geliştirilmiş bir matematiksel model önerilmiştir. Son olarak, farklı kesitlerin eğrilik sünekliğine etki eden parametreleri değerlendirmek için parametrik bir çalışma yapılmıştır. Bu çalışmanın sonuçları, şu anda mevcut olana karşı önerilende önemli bir gelişme göstermiştir. Ayrıca, geliştirilen program hem ETABS hem de Xtract ile karşılaştırıldığında moment eğriliğini iyi bir doğrulukla tanımlayabiliyordu. Ayrıca, parametrik çalışmanın sonuçları, kullanılan betonun sarılma seviyesi ve çekme mukavemeti üzerinde kesit sünekliğinin önemli bir bağımsızlığını ortaya koymuştur. Bu çalışmanın, betonarme bölümlerin davranışını güvenilir bir şekilde tahmin ederek mühendislere günlük işlerinde yardımcı olması beklenmektedir.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL INTRODUCTION

Over the last decades, the philosophy behind designing of reinforced concrete (RC) structures has developed significantly. Nowadays, the main requirement for accepting the design of a given RC section is the fact that it follows a ductile behavior in order to avoid a brittle failure of the structure. This is generally done through ensuring an adequate curvature in the ultimate limit state. The definition of ductility is the ability of members to undergo deformations without a significant decrease in its flexural capacity (Park & Ruitong, 1988) [1]. Currently, one of the most common methods to quantify the ductility of RC members is through curvature ductility. Several approaches were previously introduced to the literature for calculating this parameter taking several factors into account such as the reinforcement ratio, strength of both steel reinforcement and the concrete one, and the size of the RC section. Furthermore, some parametric studies were conducted upon these computational approaches. However, there are some problems in these methods such as their capability to be applied in all reinforcement ratios including the amount of tensile reinforcement as well as compressive reinforcement. Thus, a detailed study is important to improve these models by proposing an alternative analytical model that can overcome the current lacks in these models.

1.2 AIM OF THE STUDY

This study is intended to firstly develop a software that can define the moment curvature of RC columns and walls, secondly, propose an improved analytical approach for estimating the curvature ductility of these sections, and finally, conduct a parametric study that can highlights the influence of several factors including the strength of steel and concrete used, the rate of axial load applied, and dimensions of the RC section on the ductility. This information is of importance for both practicing structural engineers as well as scientists in the working in the field.

1.3 OUTLINE OF THE THESIS

The thesis herein consists of five main chapters of which the main scientific content is delivered. The first chapter introduce the topic by providing a general introduction and defines the aim of the study. The second chapter gives a detailed literature review of the current approaches used and highlights the findings of previous studies. Thereafter, the third chapter includes the research methodology that was followed while conducting the investigations and the main assumptions. Then the results and discussions are given in the fourth chapter of which the findings of this study will be illustrated and compared to previous ones available in the current state of the art. Finally, the major conclusions of this study are drawn in the fifth chapter and the thesis is ended with a brief information on the possible future works.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter, a detailed review of the current state of the art on the analytical modeling of behavior of RC sections will be presented. Furthermore, previous approaches computing the curvature ductility will be summarized.

2.2 CURVATURE DUCTILITY

The ductility of reinforced concrete sections is very important, since it is essential to avoid a brittle failure of the structure by ensuring adequate curvature at the ultimate limit state. According to Olivia & Mandal (2015) [2], ductile behavior in a structure can be achieved using plastic hinges positioned at appropriate locations throughout the structural frame. The ductility of plastic hinges can be obtained from the Moment – Curvature relationship of a reinforced concrete section by dividing the curvature at ultimate point on the curvature at yielding point. Where, yielding curvature is the point when tensile reinforcement yields, and ultimate curvature is the curvature value when the furthest compressed concrete fiber is crushed. Olivia & Mandal (2015) [2] suggested a formula for yielding curvature for a reinforced concrete section:

$$\emptyset_y = \frac{f_y}{E_s(1-k)d}$$

$$k = \sqrt{(\rho+\rho')^2\, n^2 + 2\left(\rho + \frac{\rho'\, d'}{d}\right)n} - (\rho+\rho')n$$

$$\rho = \frac{A_s}{b\ d}\ , \rho' = \frac{A'_s}{b\ d}\ , n = \frac{E_s}{E_c}$$

where $\emptyset_y$ is yielding curvature, *d* is effective depth of tensile reinforcement, and *n* is modular ratio. And they suggested another formula for ultimate curvature:

$$\emptyset_u = \frac{\varepsilon_{cu}\ \beta_1}{a}$$

$$a = \frac{A_s\ f_y - A'_s\ f_y}{0.85\ f'_c\ b}$$

where $\emptyset_u$ is ultimate curvature, *a* is the depth of equivalent rectangular stress block, *b* is the cross-section width, and β_1 is the ratio of the height of equivalent rectangular concrete compressive stress block to neutral axis. And according to ACI 318M-08 the value of β_1 can be calculated as follows:

$$\beta_1 = 0.85\ ; f'_c \leq 28\ MPa$$

$$\beta_1 = 0.85 - 0.007(f'_c - 28) \geq 0.65\ ; f'_c > 28\ MPa$$

The previous ultimate curvature formula assumes the compression reinforcement reaches yielding point before failure, this cannot occur except in case of a very small compression reinforcement ratio to a relatively high tensile reinforcement ratio, otherwise the formula gives greater values than actual and in the case of symmetric reinforced section without axial force and middle reinforcement, formula gives infinite ductility which does not coincide with reality. And this point will be discussed furthermore later in this research.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 INTRODUCTION

In this section detailed discussions on the material properties used in the case studies and program development stages will be provided. Furthermore, the research strategy followed in the study will be highlighted.

3.2 STRESS-STRAIN BEHAVIOR OF CONCRETE

3.2.1 Unconfined Concrete

In previous studies several empirical equations were proposed to represent the stress-strain behavior of plain concrete with various compressive strengths after series of experimental tests. The proposed empirical stress-strain equations were compared with experimental results under axial compression and showed good agreements. Although, the stress-strain relationship of these equations showed a bit difference when compared with each other, and that is because of the parameters defining the relationship depend on the testing conditions. A simple formula proposed by Carreira et al. (1985) [3] for low strength and normal strength concrete:

$$\frac{f}{f_o} = \frac{R\left(\frac{\varepsilon}{\varepsilon_o}\right)}{1 + (R-1)\left(\frac{\varepsilon}{\varepsilon_o}\right)^{\beta}}$$

$$\beta = \frac{R}{R-1} \quad , \qquad R = \frac{E_c}{E_o} \quad , \qquad E_o = \frac{f_o}{\varepsilon_o}$$

Where R is material parameter depending on the shape of the stress-strain curve, a value of $R=1.90$ was proposed later as a constant value, upon this, the last equation was modified to be as follow:

$$\frac{f}{f_o} = \frac{1.9\left(\frac{\varepsilon}{\varepsilon_o}\right)}{1 + 0.9\left(\frac{\varepsilon}{\varepsilon_o}\right)^{2.1}}$$

3.2.2 Confined Concrete

The main objectives of transverse reinforcement are (preventing buckling of longitudinal bars, resisting shear forces, and providing sufficient ductility for concrete section). In addition, confinement plays an important role in increasing the concrete compressive strength by resisting the lateral strain of the cross section. The lateral confinement of concrete resists the lateral strain by applying lateral pressure force, where the largest stress at ties location and the smallest stress at the middle distance between ties. Since lateral deformation is related to axial deformation according to Poison's ratio, it leads to a reduction in the axial strain, which is observed as an increment in concrete compressive strength. The increment in compressive strength of concrete is determined as a proportion of the lateral confinement pressure. A model was proposed by Saatcioglu and Razvi (1992) [4] based on experimental tests then modified later by Suzuki et al. (2004) [5]. The Suzuki's study has discussed the effect of the most important two parameters, volumetric ratio of transverse reinforcement and yield strength of transverse reinforcement as shown in Figure 1, Figure 2, and Figure 3.

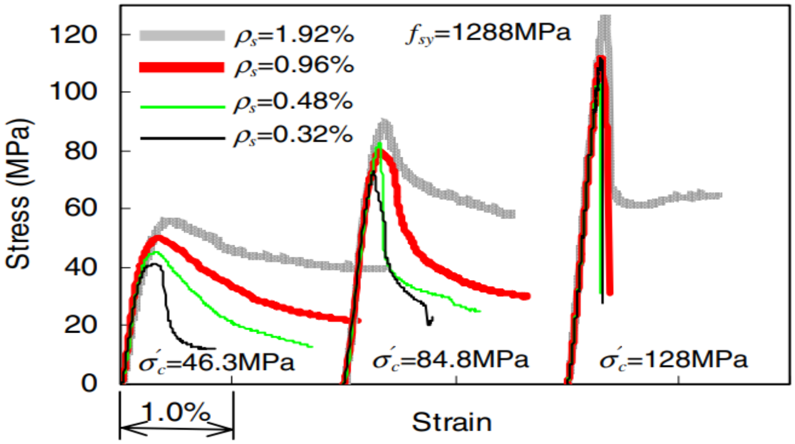


Figure 1: Effect of tie volumetric ratio

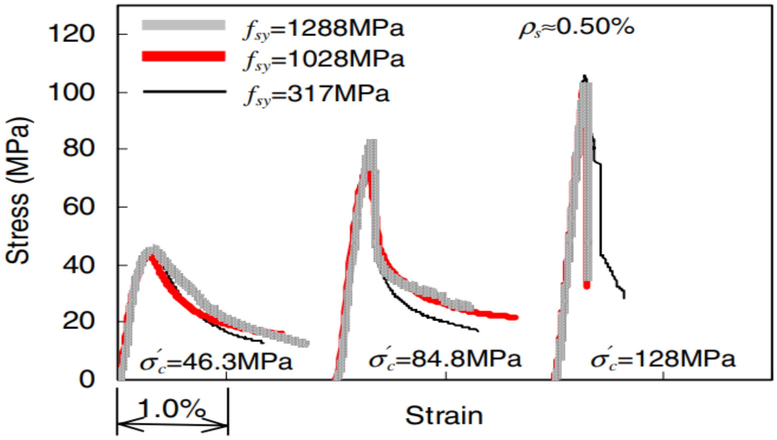


Figure 2: Effect of tie yield strength

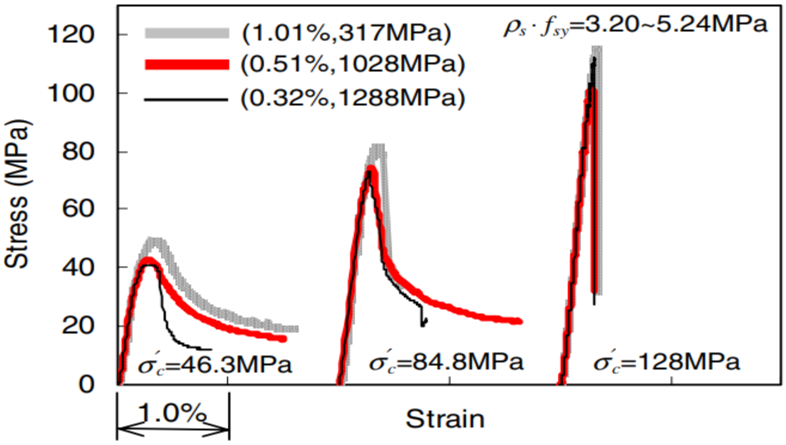


Figure 3: Effect of $\rho_s . f_{sy}$

Since the lateral pressure is distributed uniformly, the effective confinement index was defined as the uniform effective lateral pressure as in the following equation:

$$p_e = k_e\, \rho_w\, f_{s,c}$$

where ρ_w is the area ratio of transverse reinforcement; $f_{s,c}$ is the stress in transverse reinforcement at the peak strength and k_e is the effective confinement coefficient given by:

$$k_e = \frac{\left(1 - \Sigma \frac{(\omega_i)^2}{6\, b_c\, d_c}\right)\left(1 - \frac{s'}{2\, b_c}\right)\left(1 - \frac{s'}{2\, d_c}\right)}{1 - \rho_{cc}}$$

where ω_i is the clear spacing between adjacent longitudinal steel bars in a rectangular section; s' is the clear spacing of ties; b_c and d_c are the widths of concrete core; and ρ_{cc} is the longitudinal reinforcement ratio in core section. The model was based on the equivalent uniform confinement pressure concept for square cross section having the same confinement pressure in two orthogonal directions. Therefore, in the case of rectangular section with different confinement pressure in both directions, the average effective pressure can be obtained after calculating the effective lateral pressure in each direction as follow:

$$p_e = \frac{p_{ex}\, b_c + p_{ey}\, d_c}{b_c + d_c}$$

A regression analysis was performed on all test results to formulate the peak strength (σ_{cc}), the strain at peak strength (ε_{cc}), and the slope of the descending branch (E_{des}) in terms of p_e. The results of regression analyses are presented as follows:

$$\frac{\sigma_{cc}}{\sigma_{co}} = 1.0 + 4.1\left(\frac{p_e}{\sigma_{co}}\right)^{0.7}$$

$$\varepsilon_{cc} = \varepsilon_{co} + 0.015\left(\frac{p_e}{\sigma_{co}}\right)^{0.56}$$

$$E_{des} = 0.026\,\frac{\sigma_{co}^3}{p_e^{0.4}}$$

$$\sigma_{co} = 0.85\, \sigma_c'$$

$$\varepsilon_{co} = 0.0028 - 0.0008\, k_3$$

$$k_3 = \frac{40}{\sigma_{co}} \leq 1.0$$

Where $\sigma_{co}$and $\varepsilon_{co}$are the peak stress and corresponding strain of unconfined concrete. The study proposed a trial-and-error method for calculating the stress in confinement ties. And for simplicity, the study proposed a direct equation:

$$f_{s,c} = E_s\left(0.45\,\varepsilon_{co} + 0.73\left(\frac{k_e\,\rho_w}{\sigma_{co}}\right)^{0.7}\right) \leq f_{sy}$$

The strain-strain relationship of confined concrete was plotted according to a model proposed by Shah et al. (1985) [6], where the ascending part is represented by:

$$\sigma_c = \sigma_{cc}\left(1 - \left(1 - \frac{\varepsilon_c}{\varepsilon_{cc}}\right)^{\alpha}\right) \quad ; (0 \leq \varepsilon_c \leq \varepsilon_{cc})$$

$$\alpha = E_c\,\frac{\varepsilon_{cc}}{\sigma_{cc}}$$

$$E_c = 3320\,\sqrt{\sigma_{co}} + 6900$$

And the descending part was defined as a straight line connecting the point of peak strength and the point at which the stress drops to 85% of peak strength:

$$\sigma_c = \sigma_{cc} - E_{des}\,(\varepsilon_c - \varepsilon_{cc}) \quad ; (\varepsilon_{cc} \leq \varepsilon_c < \varepsilon_{ccu})$$

The study compares numerical results with experimental results for different compressive strengths of concrete, and they were in a good agreement as shown in Figure 4, Figure 5, and Figure 6.

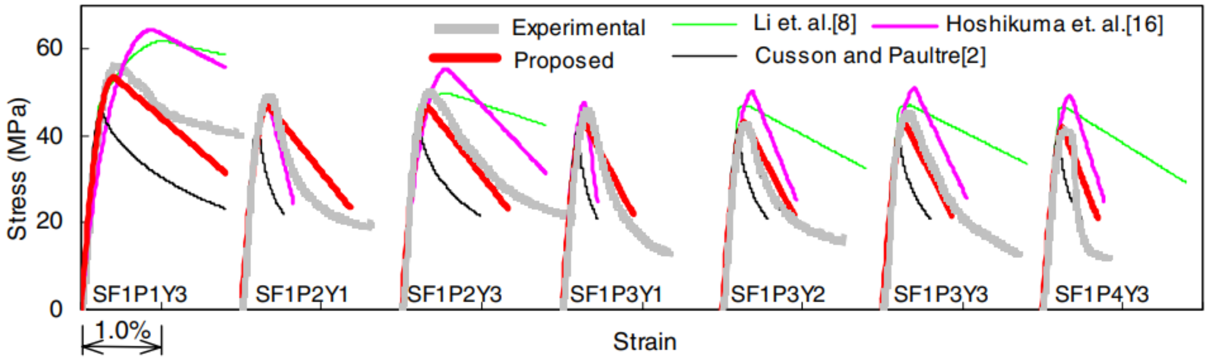


Figure 4: Comparison of stress-strain models ($\sigma_c' = 46.3\ MPa$)

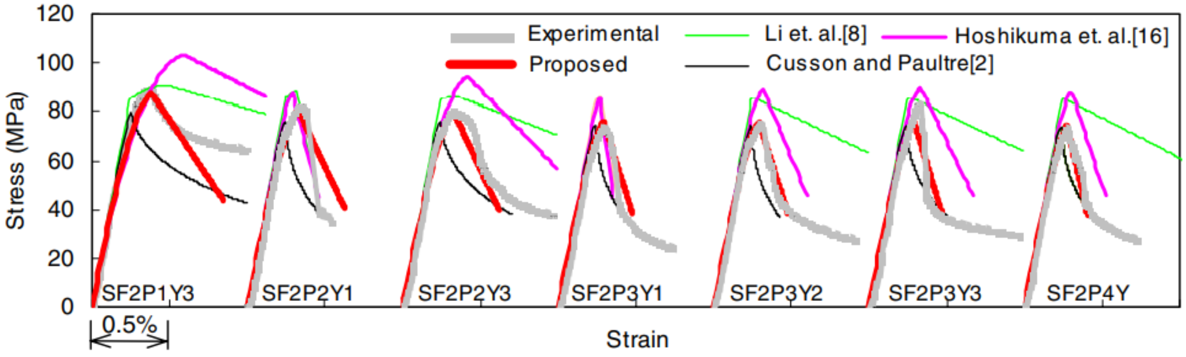


Figure 5: Comparison of stress-strain models ($\sigma_c' = 84.8\ MPa$)

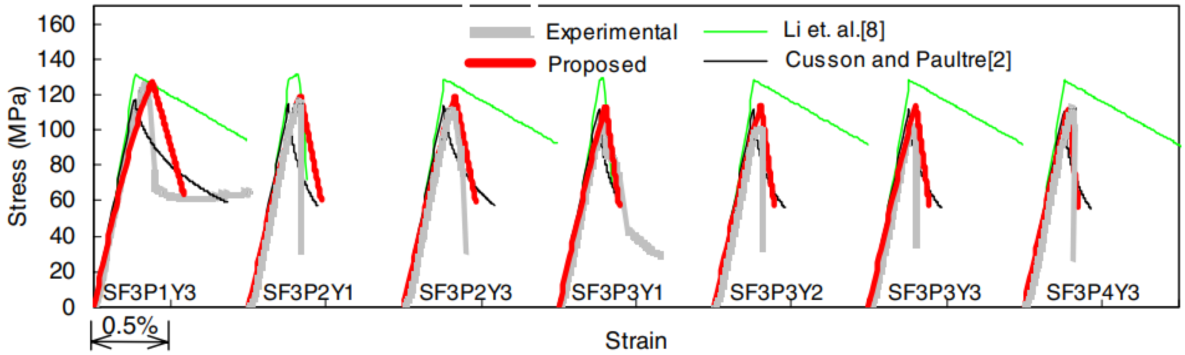


Figure 6: Comparison of stress-strain models ($\sigma_c' = 128\ MPa$)

Another recent model was proposed by Legeron and Paultre (2003) [7] to describe the behavior of confined concrete based on Mander et al. (1988) [8] model. The analytical model was compared with a wide range of concrete columns with concrete strength ranging from 30 to 120 MPa confined with steel of yield strength ranging from 250 to 1,400 MPa.

$$f'_{le} = \frac{K_e\left(A_{shy}\, f'_h\right)}{c_y\, s}$$

$$K_e = \frac{\left(1 - \frac{\sum w_i^2}{6\, c_x\, c_y}\right)\left(1 - \frac{s'}{2c_x}\right)\left(1 - \frac{s'}{2c_y}\right)}{1 - \rho_{cc}} \geq 0$$

$$f'_h = \begin{Bmatrix} f_{hy} & for\;\; \kappa \leq 10 \\ \dfrac{0.25\, f'_c}{\rho_{sey}\, (\kappa - 10)} \geq 0.43\, \varepsilon'_c\, E_s \ngtr f_{hy} & for\;\; \kappa > 10 \end{Bmatrix}$$

$$\kappa = \frac{f'_c}{\rho_{sey}\, E_s\, \varepsilon'_c}$$

$$\rho_{sey} = K_e\, \rho_{sy}$$

$$f_{cc} = f_{co}\left(-1.254 + 2.254\sqrt{1 + \frac{7.94 f'_l}{f_{co}}} - \frac{2 f'_l}{f_{co}}\right)$$

Where K_e is the geometric confinement effectiveness coefficient, which measures the effectiveness of the confinement reinforcement of confined concrete and varies from 1 for a continuous tube to 0 when ties are spaced more than half the core cross section minimum dimension; A_{shy} is the total section of confinement reinforcement for the set of ties in direction *y*; c_y is the cross section dimension in direction *y*, measured center-to-center of peripheral ties; *s* center-to-center spacing between ties; and f'_h is the stress in the confinement reinforcement at peak stress. According to the author, the stress strain curve can be predicted by three coordinates. The ascending part between zero and the first coordinate can be derived by an equation based on Sargin et al. equation (1968) [9]:

$$\sigma_{cc} = f_{cc} \times \frac{k_c \times \bar{\varepsilon_c} + (k'_c - 1) \times \bar{\varepsilon_c}^2}{1 + (k_c - 2) \times \bar{\varepsilon_c} + k'_c \times \bar{\varepsilon_c}^2}\;;0 \leq \varepsilon_c \leq \varepsilon_{cco}$$

$$\bar{\varepsilon_c} = \frac{\varepsilon_c}{\varepsilon_{cco}} \quad , and\; \varepsilon_{cco} = \varepsilon_{co} \times \left[1 + 5\left(\frac{f_{cc}}{f_{co}} - 1\right)\right]$$

$$k_c = \frac{E_{bco} \times \varepsilon_{cco}}{f_{cc}} \ \ , \ \ E_{bco} = 11000\sqrt[3]{f_{cc}} \ \ , \ \ and\ k_c' = k_c - 1$$

The descending part between the first and the second coordinates can be determined by:

$$\sigma_{cc} = f_{cc} - E_{sc}(\varepsilon_c - \varepsilon_{cco}) \ ; \ \varepsilon_{cco} < \varepsilon_c \leq \varepsilon_{65}$$

$$E_{sc} = \frac{6 \times f_{co}^2}{k_e \times \rho_s \times f_{yh}}$$

$$\varepsilon_{65} = \frac{0.35 \times f_{cc}}{E_{sc}} + \varepsilon_{cco}$$

where E_{sc} is the slope of the descending part and ε_{65} is the strain at 65% of confined peak stress. After reaching the strain ε_{65}, the stress of confined concrete has a constant value of $0.65f_{cc}$ until the ultimate strain (ε_{ccu}).

$$\varepsilon_{ccu} = 0.4\frac{f_l}{f_{co}} + \varepsilon_{cu}$$

3.2.3 Tensile Strength of Concrete

Concrete is a brittle material and weak under tension, therefore it is used to resist compression mainly and the tensile strength of concrete is usually neglected due to its small value compared to compressive strength. However, in this research the effect of tensile strength of concrete on bending capacity and curvature ductility of structural elements subjected to bending moment and axial force will be discussed. According to Jaber et al. (2018) [10], some laboratory split experiments were conducted, and it was noticed that split tensile strength was linearly related to compressive strength of concrete as follow:

$$f_{spt} = k\ f_c'^{\,n}$$

where k and n are constants and various values have been proposed by several researchers and codes based on experimental results. The following table shows some of these values:

Table 1: Values of k and n

Source	k	n
ACI 318	0.56	0.50
ACI 363R	0.59	0.50
Gardner	0.47	0.59
Nihal	0.387	0.63
JCI	0.13	0.85
JSCE	0.23	0.67
CEB-FIB	0.30	0.67
Raphael	0.313	0.667
Ahmad and Shah	0.462	0.55
Oloukun et al.	0.294	0.69

The tensile concrete strength is highly affected by the shape of the applied force and the used experiment. There are three forms of tensile strength, and they are splitting tension, direct tension, and tension under bending. Karadogan et al. (2015) [11] proposed two formulae for converting direct tensile strength to splitting tensile strength and tensile strength under bending as follows:

$$f_{ctk} = \frac{f_{ctk}^{y}}{1.5}$$

$$f_{ctk} = \frac{f_{ctk}^{e}}{2}$$

where f_{ctk}^{y} is the splitting tensile strength, f_{ctk}^{e} is the tensile strength under bending, and f_{ctk} is the direct tensile strength. After substituting one equation with the other, we get the following formula:

$$f_{ctk}^{e} = \frac{4\,f_{ctk}^{y}}{3}$$

To take the effect of tensile concrete strength on bending capacity of reinforced concrete section, the value of maximum tensile strength is insufficient, thus, tensile stress-strain relationship of concrete is needed. According to Kaklauskas (1999) [12], concrete tensile stress-strain relationship consists of two parts, a linear part with a slop of concrete modules of elasticity E_c, and it is defined by the following formula:

$$\sigma_t = E_c \, \varepsilon_t$$

The first part is limited by the strain at first crack in concrete under tension ε_{cr}. The second part is nonlinear and extended to the strain value of $\beta \, \varepsilon_{cr}$. The second part is defined by the following formula:

$$\sigma_t = 0.625 \, \sigma_{cr} \left(1 - \frac{\overline{\varepsilon_t}}{\beta} + \frac{1 + 0.6 \, \beta}{\beta \, \overline{\varepsilon_t}}\right)$$

$$\overline{\varepsilon_t} = \frac{\varepsilon_t}{\varepsilon_{cr}}$$

The value of β depends on the reinforcement ratio ρ and it is defined by:

$$\beta = 32.8 - 27.6 \, \rho + 7.12 \, \rho^2$$

3.3 STEEL REINFORCEMENT

Stress-strain relationship of steel consists of two main phases, first phase is linear elastic phase with a slop of modules of elasticity E_s and limited by yielding point. After yielding point steel enters plastic phase. According to Khatulistiani et al. (2020) [13], plastic phase starts with constant stress, then a hardening stage which is extended to ultimate stress, finally steel begins losing its resistance until failure, the following fig shows the stress strain curve of steel:

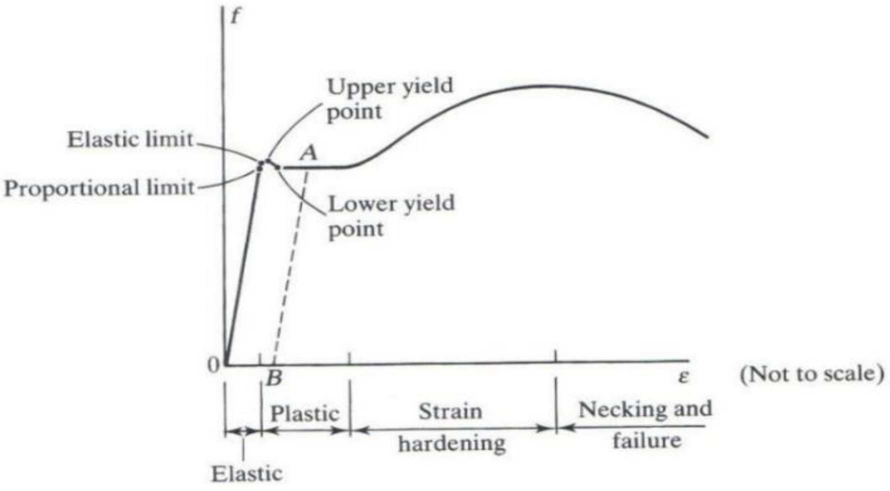


Figure 7: Idealized stress strain behavior of steel rebar

The previous curve was simplified into a bi-linear relationship consists of two phases, elastic phase and plastic phase as shown in Figure8 below:

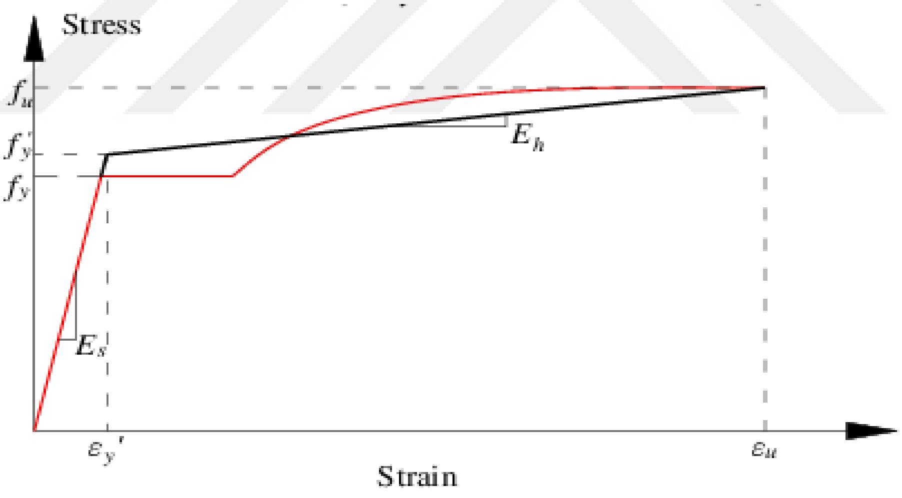


Figure 8: Stress strain behavior of steel rebar

Steel strength is affected by chemical composition. Various grades of steel will be used in this study, taken from the ASTM Standard. The following table shows the important characteristics of each steel grade, which are yield strength f_y, tensile strength f_u, and elongation ε_u. Where steel modulus of elasticity E_s has a constant value of 200 GPa.

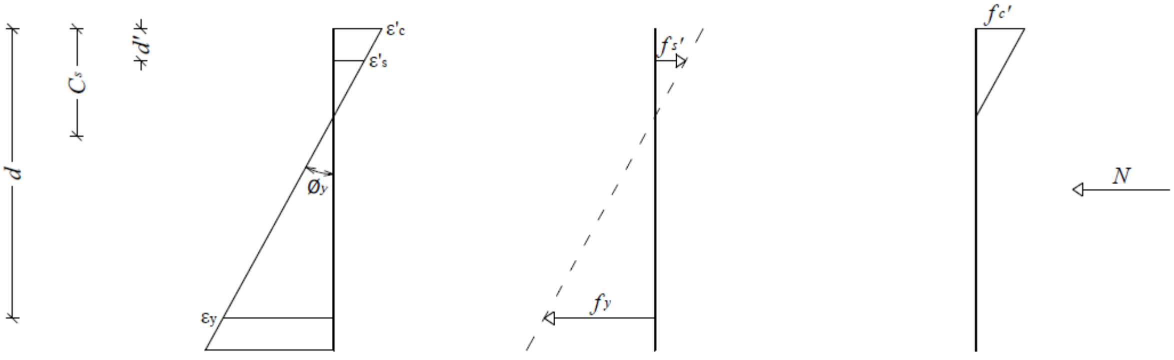
Table 2: Properties of steel in standards

	Standard	Yield Strength MPa	Tensile Strength MPa	Elongation %
GR 40	ASTM A 615	280	420	10 - 12
GR 60	ASTM A 615	420	620	7 - 9
GR 75	ASTM A 615	520	690	6 - 7
GR 100	ASTM A 709	690	760	18

3.4 MOMENT-CURVATURE CURVE

Moment-curvature curve of a reinforced concrete section is the relationship between bending moment resistance and its rotation around the neutral axis in terms of one per meter, either subjected to an axial force or not. Plotting the moment-curvature curve could be done by calculating the moment resistance at each curvature value, starting from a very small curvature, and increasing it gradually until failure where the moment resistance is zero. The following section discusses the derivation of curvature ductility equation in details.

- Curvature at yielding point:



$$N + f_y\, A_s = f_s'\, A_s' + 0.5\, f_c'\, C_s\, B$$

$$\emptyset_y = \frac{\varepsilon_y}{d - C_s} \rightarrow C_s = d - \frac{\varepsilon_y}{\emptyset_y}$$

$$\varepsilon_s' = \frac{C_s - d'}{d - C_s}\,\varepsilon_y = (d - d')\,\emptyset_y - \varepsilon_y$$

$$f_s' = E_s\,\varepsilon_s' = E_s(d - d')\,\emptyset_y - E_s\,\varepsilon_y = E_s(d - d')\,\emptyset_y - f_y$$

$$\varepsilon_c' = d\,\emptyset_y - \varepsilon_y$$

$$f_c \cong E_c\,\varepsilon_c' = E_c\,d\,\emptyset_y - E_c\,\varepsilon_y$$

$$N + f_y\,A_s = E_s\,A_s'\,(d - d')\,\emptyset_y - f_y\,A_s' + 0.5\,f_c\,B\,d - 0.5\,f_c\,B\,\frac{\varepsilon_y}{\emptyset_y}$$

$$N\,\emptyset_y + f_y\,A_s\emptyset_y + E_s\,A_s'\,(d' - d)\,\emptyset_y^2 + f_y\,A_s'\,\emptyset_y - 0.5\,f_c\,B\,d + 0.5\,f_c\,B\,\varepsilon_y = 0$$

$$N\,\emptyset_y + f_y\,A_s\emptyset_y + E_s\,A_s'\,(d' - d)\,\emptyset_y^2 + f_y\,A_s'\,\emptyset_y - 0.5\,B\,E_c\,d^2\,\emptyset_y^2 + B\,E_c\,d\,\varepsilon_y\,\emptyset_y$$
$$- 0.5\,B\,E_c\,\varepsilon_y^2 = 0$$

$$\left[E_s\,A_s'\,(d' - d) - 0.5\,B\,E_c\,d^2\right]\emptyset_y^2 + \left[N + f_y\,(A_s + A_s') + B\,E_c\,d\,\varepsilon_y\right]\emptyset_y + \left[-0.5\,B\,E_c\,\varepsilon_y^2\right] = 0$$

$$\left[-0.5\,B\,E_c\,d^2\right]\emptyset_y^2 + \left[N + f_y\,A_s + B\,E_c\,d\,\varepsilon_y\right]\emptyset_y + \left[-0.5\,B\,E_c\,\varepsilon_y^2\right] = 0$$

$$[-0.5]\,\emptyset_y^2 + \left[\frac{N + f_y\,A_s + B\,E_c\,d\,\varepsilon_y}{B\,E_c\,d^2}\right]\emptyset_y + \left[\frac{-0.5\,\varepsilon_y^2}{d^2}\right] = 0$$

$$[-0.5]\,\emptyset_y^2 + \left[\frac{N + f_y\,A_s}{B\,E_c\,d^2} + \frac{\varepsilon_y}{d}\right]\emptyset_y + \left[0.5\,\left(\frac{\varepsilon_y}{d}\right)^2\right] = 0$$

$$[-0.5]\,\emptyset_y^2 + \left[\frac{N + f_y\,A_s}{B\,E_c\,d^2} + \frac{f_y}{E_s\,d}\right]\emptyset_y + \left[0.5\,\left(\frac{f_y}{E_s\,d}\right)^2\right] = 0$$

$$a = -0.5$$

$$b = \frac{N + f_y\,A_s}{B\,E_c\,d^2} + \frac{f_y}{E_s\,d}$$

$$c = 0.5\,\left(\frac{f_y}{E_s\,d}\right)^2$$

$$\emptyset_y = \frac{-\sqrt{b^2 - 4\,a\,c} - b}{2a} = \sqrt{b^2 + 2\,c} + b$$

$$\propto_1^2 = 2\,c$$

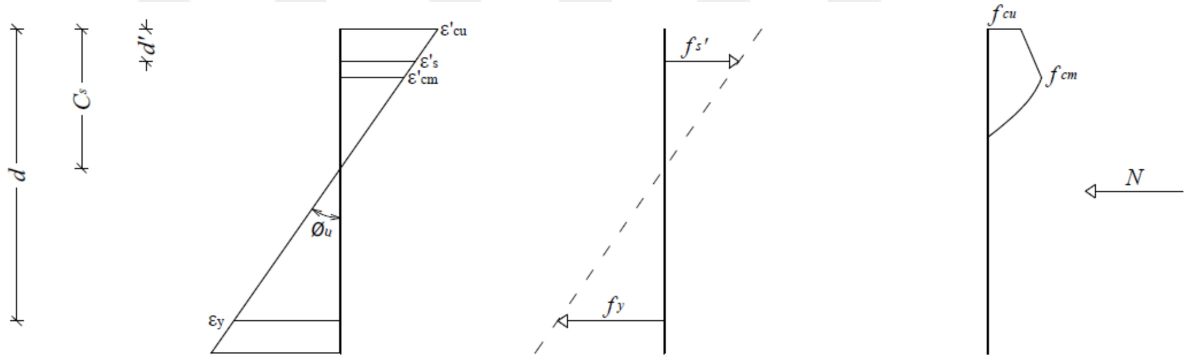
$$\propto_2 = b$$

$$\propto_1 = \frac{f_y}{E_s \cdot d}$$

$$\propto_2 = \frac{N + f_y \cdot A_s}{B \cdot d^2 \cdot E_c} + \propto_1$$

$$\emptyset_y = \sqrt{\propto_2^2 - \propto_1^2} + \propto_2$$

- Curvature at ultimate point:



$$N + f_s\,A_s = f_s'\,A_s' + \frac{f_{cu} + f_{cm}}{2}\;y\,B + \frac{2}{3} f_{cm}\,(C_s - y)\,B$$

$$y = C_s\left(1 - \frac{\varepsilon_{cm}}{\varepsilon_{cu}}\right)$$

$$C_s = \frac{\varepsilon_{cu}}{\emptyset_u}$$

$$y = \frac{\varepsilon_{cu}}{\emptyset_u}\left(1 - \frac{\varepsilon_{cm}}{\varepsilon_{cu}}\right) = \frac{\varepsilon_{cu}}{\emptyset_u} - \frac{\varepsilon_{cu}\,\varepsilon_{cm}}{\varepsilon_{cu}\emptyset_u} = \frac{\varepsilon_{cu} - \varepsilon_{cm}}{\emptyset_u}$$

$$\varepsilon_s = \frac{(d - C_s)\varepsilon_{cu}}{C_s} = \frac{d\,\varepsilon_{cu}}{C_s} - \frac{C_s\,\varepsilon_{cu}}{C_s} = d\,\varepsilon_{cu}\left(\frac{\emptyset_u}{\varepsilon_{cu}}\right) - \varepsilon_{cu} = d\,\emptyset_u - \varepsilon_{cu}$$

$$(C_s - y) = \frac{\varepsilon_{cu}}{\emptyset_u} - \frac{\varepsilon_{cu} - \varepsilon_{cm}}{\emptyset_u} = \frac{\varepsilon_{cm}}{\emptyset_u}$$

$$\varepsilon_s' = \frac{(C_s - d')\varepsilon_{cu}}{C_s} = \frac{C_s\,\varepsilon_{cu}}{C_s} - \frac{d'\,\varepsilon_{cu}}{C_s} = \varepsilon_{cu} - d'\,\varepsilon_{cu}\left(\frac{\emptyset_u}{\varepsilon_{cu}}\right) = \varepsilon_{cu} - d'\,\emptyset_u$$

$$f_s' = E_s\,\varepsilon_s' = E_s(\varepsilon_{cu} - d'\,\emptyset_u) = E_s\,\varepsilon_{cu} - d'\,E_s\,\emptyset_u$$

$$f_s = f_y + \frac{(\varepsilon_s - \varepsilon_y)(f_u - f_y)}{(\varepsilon_u - \varepsilon_y)} \cong f_y$$

$$N + f_y\,A_s = E_s\,\varepsilon_{cu}\,A_s' - d'\,E_s\,A_s' + \frac{f_{cu} + f_{cm}}{2}\,\frac{\varepsilon_{cu} - \varepsilon_{cm}}{\emptyset_u}\,B + \frac{2}{3} f_{cm}\,\frac{\varepsilon_{cm}}{\emptyset_u}\,B$$

$$N\,\emptyset_u + f_y\,A_s\,\emptyset_u - E_s\,\varepsilon_{cu}\,A_s'\,\emptyset_u + d'\,E_s\,A_s'\,\emptyset_u^2 - \frac{(f_{cu} + f_{cm})(\varepsilon_{cu} - \varepsilon_{cm})\,B}{2} - \frac{2}{3}\,f_{cm}\,\varepsilon_{cm}\,B = 0$$

$$[d'\,E_s\,A_s']\emptyset_u^2 + [N + f_y\,A_s - E_s\,\varepsilon_{cu}\,A_s']\emptyset_u + \left[-\frac{3(f_{cu} + f_{cm})(\varepsilon_{cu} - \varepsilon_{cm})\,B}{6} - \frac{4}{6}\,f_{cm}\,\varepsilon_{cm}\,B\right] = 0$$

$$[d'\,E_s\,A_s']\emptyset_u^2 + [N + f_y\,A_s - E_s\,\varepsilon_{cu}\,A_s']\emptyset_u + \left[\frac{-3(f_{cu} + f_{cm})(\varepsilon_{cu} - \varepsilon_{cm})\,B - 4\,f_{cm}\,\varepsilon_{cm}\,B}{6}\right] = 0$$

$$0.5\,\emptyset_u^2 + \left[\frac{N + f_y\,A_s - E_s\,\varepsilon_{cu}\,A_s'}{2\,d'\,E_s\,A_s'}\right]\emptyset_u + \left[\frac{-3(f_{cu} + f_{cm})(\varepsilon_{cu} - \varepsilon_{cm})\,B - 4\,f_{cm}\,\varepsilon_{cm}\,B}{12\,d'\,E_s\,A_s'}\right] = 0$$

$$\varepsilon_{cm} = 0.5\,\varepsilon_{cu} \sim 0.9\,\varepsilon_{cu}$$

$$f_{cu} = 0.2\,f_{cm} \sim 0.8\,f_{cm}$$

$$0.5\,\emptyset_u^2 + \left[\frac{N + f_y\,A_s - E_s\,\varepsilon_{cu}\,A_s'}{2\,d'\,E_s\,A_s'}\right]\emptyset_u + \left[\frac{-8.7\,f_{cm}\,\varepsilon_{cu}\,B}{12\,d'\,E_s\,A_s'}\right] = 0$$

$$0.5\,\emptyset_u^2 + \left[\frac{N + f_y\,(A_s + A_s'')}{2\,d'\,E_s\,A_s'} - \frac{\varepsilon_{cu}}{2\,d'}\right]\emptyset_u + \left[\frac{-f_{cm}\,\varepsilon_{cu}\,B}{1.38\,d'\,E_s\,A_s'}\right] = 0$$

$$d' \cong 40$$

$$0.5\,\emptyset_u^2 + \left[\frac{N + f_y\,(A_s + A_s'')}{16\,A_s'\,10^6} - \frac{\varepsilon_{cu}}{80}\right]\emptyset_u + \left[\frac{-f_{cm}\,\varepsilon_{cu}\,B}{22\,A_s' \times 10^6}\right] = 0$$

$$a = 0.5$$

$$b = \frac{N + f_y\,(A_s + A_s'')}{16\,A_s'\,10^6} - \frac{\varepsilon_{cu}}{80}$$

$$c = \frac{-f_{cm}\ \varepsilon_{cu}\ B}{22\ A'_s \times 10^6}$$

$$\emptyset_u = \frac{\sqrt{b^2 - 4\ a\ c} - b}{2a} = \sqrt{b^2 - 2\ c} - b$$

$$\propto_3 = -\ 2\ c$$

$$\propto_4 = b$$

$$\propto_3 = \frac{\varepsilon_{cu} \cdot f_{cm} \cdot B}{11 \cdot A'_s \cdot 10^6}$$

$$\propto_4 = \frac{N + f_y \cdot (A_s + A''_s)}{16 \cdot A'_s \cdot 10^6} - \frac{\varepsilon_{cu}}{80}$$

$$\emptyset_u = \sqrt{\propto_4^2 + \propto_3} - \propto_4$$

For Wall sections:

$$\propto_3 = \frac{5 \cdot \varepsilon_{cu} \cdot f_{cm} \cdot B}{H_C \cdot A'_s \cdot 10^6}$$

$$\propto_4 = \frac{N + f_y \cdot (A_s + A''_s)}{2 \cdot H_C \cdot A'_s \cdot 10^6} - \frac{\varepsilon_{cu}}{H_C}$$

Where f_y is steel bars yield strength, f_{cm} is maximum strength of concrete, E_s is modules of elasticity of steel, E_c is modules of elasticity of concrete, ε_{cu} is ultimate strain of concrete, A_s is tension bars reinforcement area, A'_s is compression bars reinforcement area, A''_s is middle bars reinforcement area, d is tension bars effective depth, B is section width, N is applied axial force, and H_C is hidden column height of shear wall.

3.5 DEVELOPED SOFTWARE

A new software for estimating and plotting the moment curvature, interaction curve, and curvature ductility of reinforced concrete sections will be developed as a part of the study. Accordingly, the MCI software was created. In general, MCI software is a program that accurately analyzes and calculates rectangular reinforced concrete components as well as shear walls in order to plot the moment curvature, interaction curve, and curvature ductility of afore-mentioned sections. This is generally done using the principles of finite element method by meshing the analyzed section into several layers. The program has several features and merits that enhances its performance as compared to other available software. These features and merits can be summarized as follows:

- Comparing the behavior of several sections at the same time.
- Evaluating the effect of various axial loads on the performance of the sections.
- Considering the effect of confinement or ignoring it for a certain section with the option of allowing a comparison of the results of both cases.
- Considering the influence of concrete in tension or ignoring it with the possibility of comparing the results together.
- Various material properties were already inserted in the database of the program for simplicity of defining the section properties. In addition, code-based equations were programed to simplify and facilitate the task of defining the material properties.
- Analyzing the section for both positive and negative bending moments with the option of comparing both cases together.
- In the case of rectangular column/beam sections, it allows the user to analyze the section in both perpendicular directions.
- It is possible to automatically identify some of the critical points on the moment curvature curve such as the one when the concrete reaches its maximum resistance and when it reaches the collapse point. In addition to that, in the case of confined concrete, the program determines and specifies the points were the concrete reaches its ultimate capacity and when the concrete crashes. On the other hand, when the tensile strength of concrete is considered, the point at

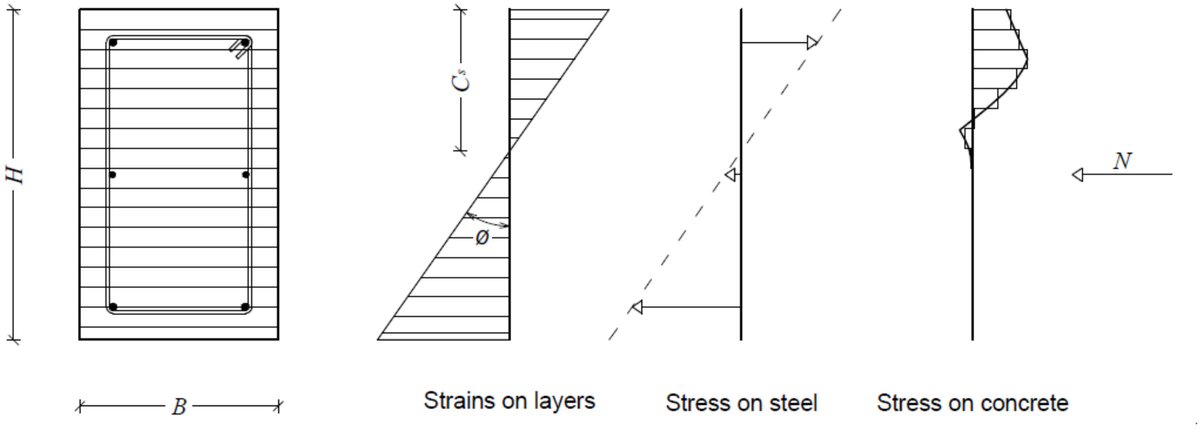
the ultimate tensile capacity and concrete failure in tension are indicated. However, in all cases, the yielding of reinforcements and their failure points are all stored in the program.

- Another important point in the developed software is its capability to present the results of the analysis after the upper layers of the concrete start crushing until total collapse of the section is achieved. This feature is not available in other software since they assume that the section has failed once crushing starts at the upper region, whereas it was found that the section can hold some capacity which can maintain its integrity for a fairly long period of time especially if the confinement is well designed until the complete collapse is reached. This case was not considered in the calculation of curvature ductility since the code presumes a total collapse once the concrete has been crushed.

Moment resistance of a cross section is the sum of the moment resistance of each material's particle around the natural axis. And because of the concrete stress strain relationship nonlinearity, the cross section will be subdivided into thin horizontal layers, assuming the stresses on each layer are uniformly distributed and equal to the stress at the middle of each layer. To find the moment resistance for a curvature value $\emptyset$, the depth of the neutral axis C_s is assumed then strain on each layer is determined as follow:

$$\varepsilon_i = \emptyset \cdot y_i$$

where y_i is the distance between neutral axis and the center of layer i. After determining strains in all layers then stresses from strass-strain relationships, the sum of the forces for each section should be satisfy the equilibrium condition. When forces throughout the cross-section are in equilibrium, the bending moment can finally be determined using trial and error method.



For this purpose, MCI computer program was developed to make these repeated calculations and allowing the user to increase the accuracy by decreasing the layer's thicknesses as much as possible. The program has many options for section and material properties as shown in Figure 10, and Figure 11. In addition, it was provided with options to involve increment in concrete compressive strength due to lateral confinement and concrete tensile strength and shows their effects on bending resistance. The following figure shows flowchart of the procedure in a loop:

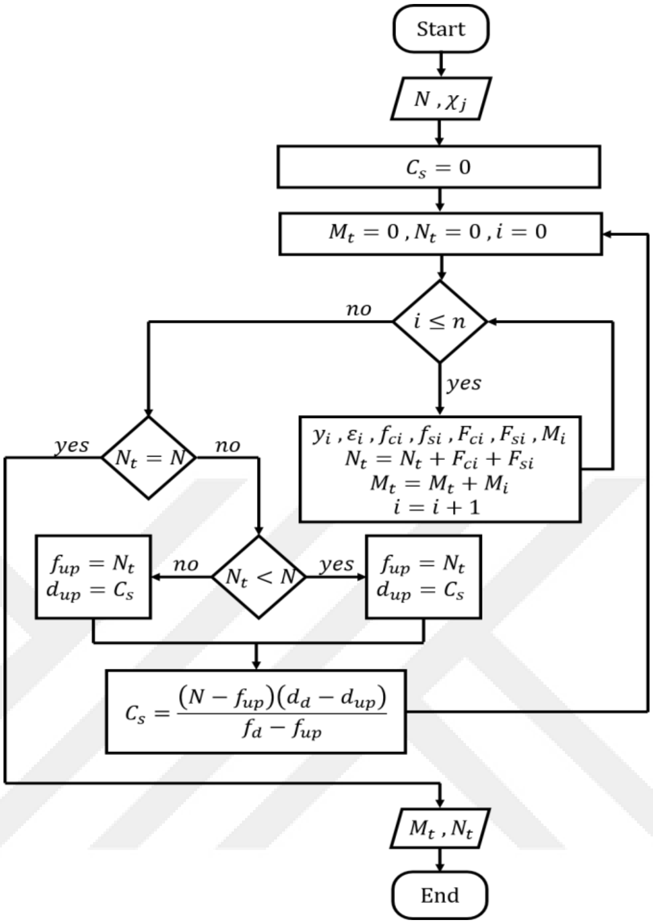
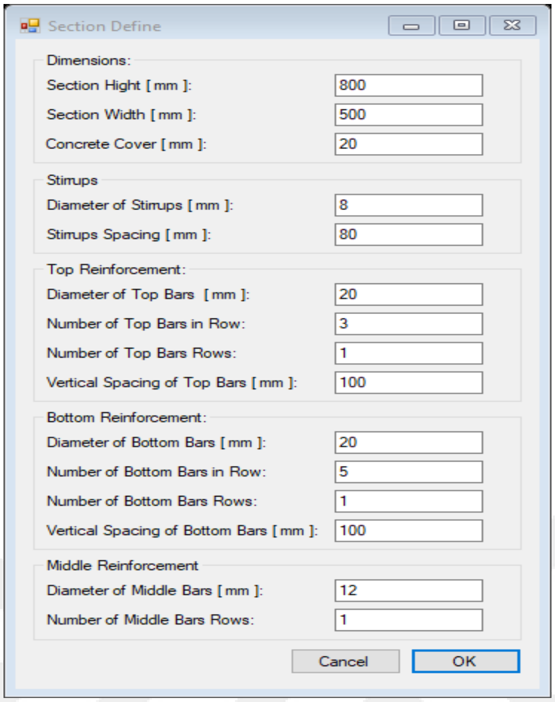


Figure 9: A flowchart of the procedure for calculating moment resistance.

Where N is the applied axial force, $\emptyset_j$ is the curvature value, C_s is the depth of neutral axis, n is the number of layers, M_t is the bending resistance of the cross section, N_t is the axial resistance, y_i is the distance between neutral axis and the center of layer i, ε_i is the strain at the center of layer i, f_{ci} is the stresses on concrete in layer i, f_{si} is the stresses on steel in layer i, F_{ci} is the concrete resistance of layer i, F_{si} is the steel resistance of layer i, and M_i is bending resistance of layer i.



Dimensions:

Section Hight [mm]: 800

Section Width [mm]: 500

Concrete Cover [mm]: 20

Stirrups

Diameter of Stirrups [mm]: 8

Stirrups Spacing [mm]: 80

Top Reinforcement:

Diameter of Top Bars [mm]: 20

Number of Top Bars in Row: 3

Number of Top Bars Rows: 1

Vertical Spacing of Top Bars [mm]: 100

Bottom Reinforcement:

Diameter of Bottom Bars [mm]: 20

Number of Bottom Bars in Row: 5

Number of Bottom Bars Rows: 1

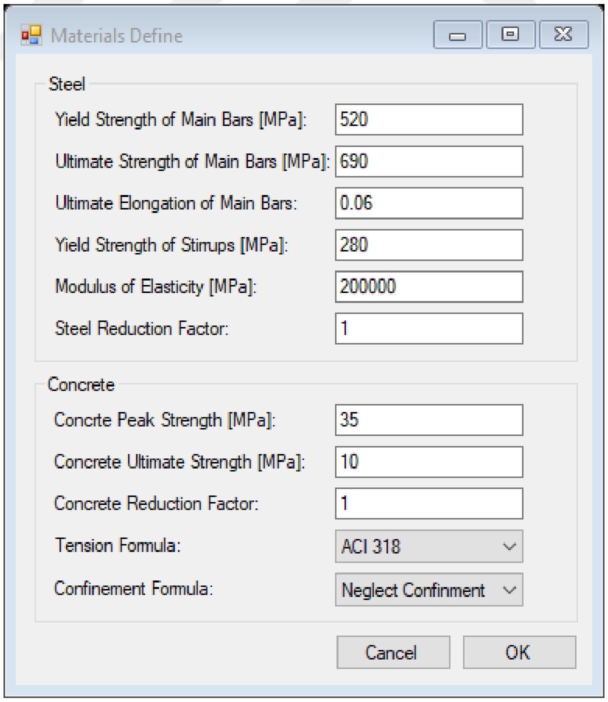
Vertical Spacing of Bottom Bars [mm]: 100

Middle Reinforcement

Diameter of Middle Bars [mm]: 12

Number of Middle Bars Rows: 1

Figure 10: A screenshot of the section define window.



Steel

Yield Strength of Main Bars [MPa]: 520

Ultimate Strength of Main Bars [MPa]: 690

Ultimate Elongation of Main Bars: 0.06

Yield Strength of Stirrups [MPa]: 280

Modulus of Elasticity [MPa]: 200000

Steel Reduction Factor: 1

Concrete

Concrte Peak Strength [MPa]: 35

Concrete Ultimate Strength [MPa]: 10

Concrete Reduction Factor: 1

Tension Formula: ACI 318

Confinement Formula: Neglect Confinment

Figure 11: A screenshot of the material define window.

After calculations are done, the previous steps will be repeated for another curvature value until the cross section is unable to carry any bending moment, the following flowchart explain the whole procedure:

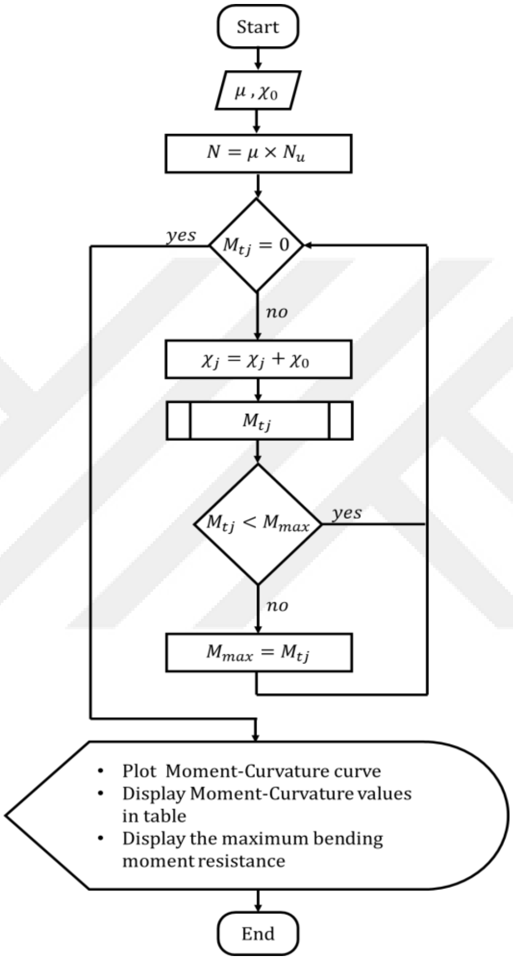


Figure 12: A flowchart of the procedure for plotting the moment curvature curve.

Where $\emptyset_0$ is curvature step, μ is the ratio between the applied axial force and the axial compressive resistance of the cross section, N_u is the axial compressive resistance of the cross section, M_{tj} is the bending resistance of the cross section under a specific axial force and curvature value, and M_{max} is the maximum bending resistance of the cross section under a specific axial force.

The outputs of the program are displayed into two forms, a table and a graph show the relationship between bending moment and curvature as shown in figure 14, and the maximum point of the moment-curvature curve represents the bending capacity of the cross section under the current applied axial force. The maximum bending capacity values for unlimited number of axial forces ranging between zero for pure bending moment to the ultimate compressive strength of the cross section represent the interaction curve as shown in figure 15. For plotting the interaction curve, the maximum bending resistances for many axial forces as proportions of the ultimate compressive strength of the cross section are determined, as shown in the following flowchart:

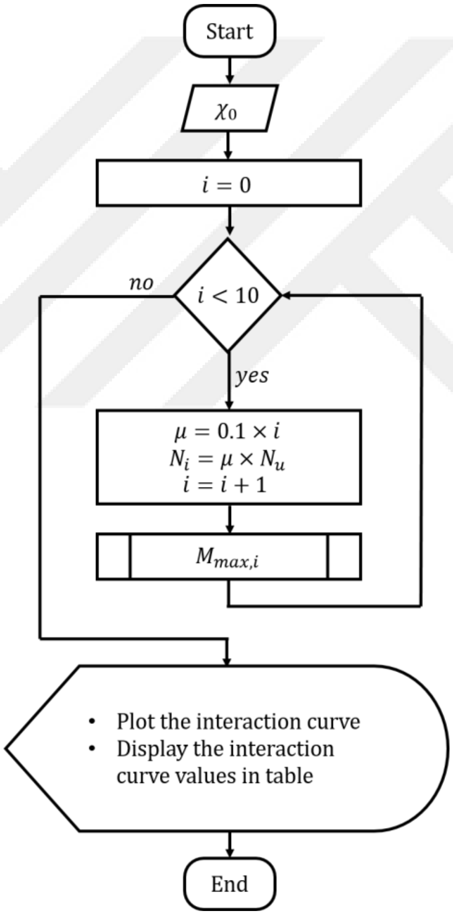
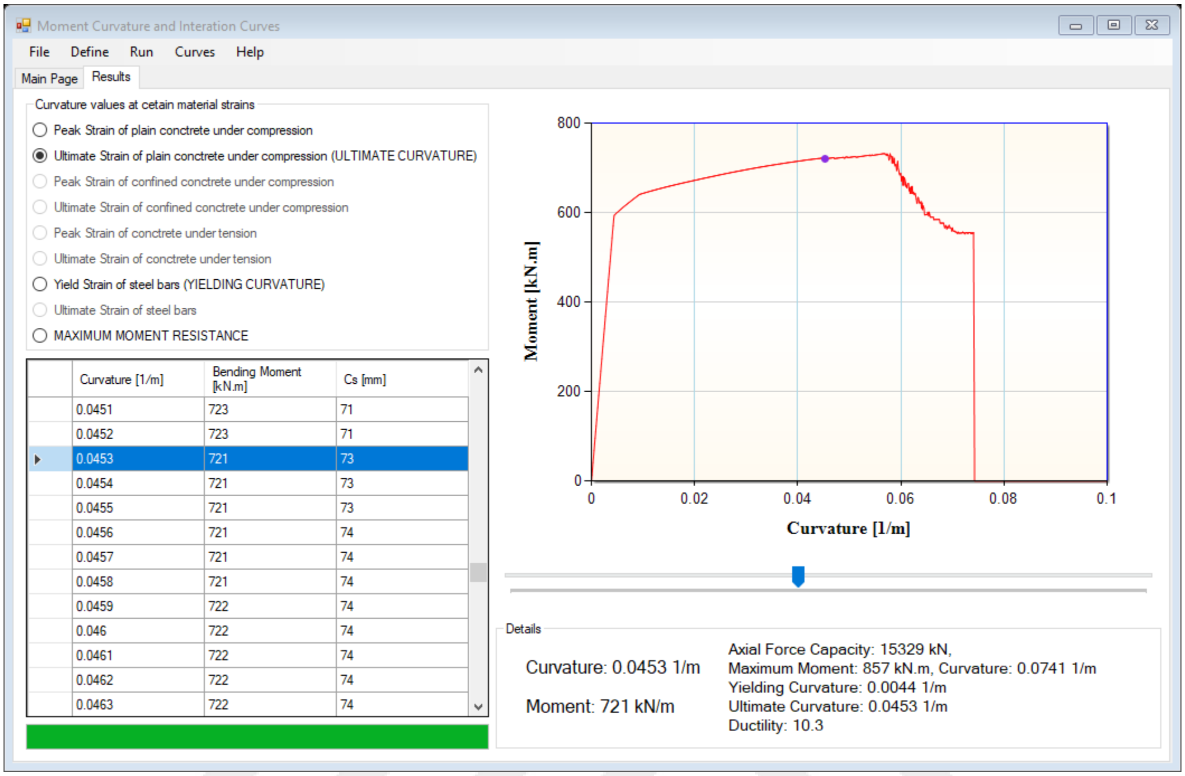


Figure 13: A flowchart of the procedure for plotting the interaction curve.

Where N_i is the applied axial force, i is the iteration number, and $M_{max,i}$ is the maximum bending resistance of the cross section under a specific axial force.



Curvature values at cetain material strains

○ Peak Strain of plain conctrete under compression
● Ultimate Strain of plain conctrete under compression (ULTIMATE CURVATURE)
○ Peak Strain of confined conctrete under compression
○ Ultimate Strain of confined conctrete under compression
○ Peak Strain of concrete under tension
○ Ultimate Strain of concrete under tension
○ Yield Strain of steel bars (YIELDING CURVATURE)
○ Ultimate Strain of steel bars
○ MAXIMUM MOMENT RESISTANCE

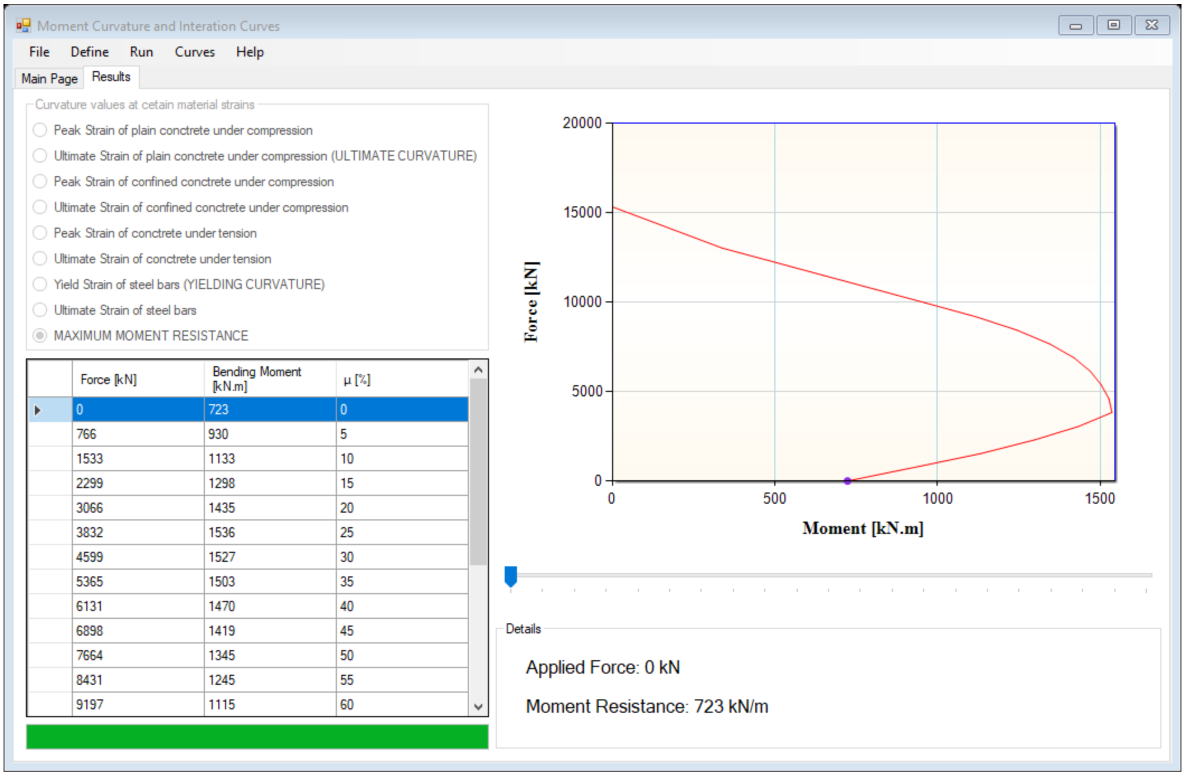
Curvature [1/m]	Bending Moment [kN.m]	Cs [mm]
0.0451	723	71
0.0452	723	71
0.0453	721	73
0.0454	721	73
0.0455	721	73
0.0456	721	74
0.0457	721	74
0.0458	721	74
0.0459	722	74
0.046	722	74
0.0461	722	74
0.0462	722	74
0.0463	722	74

Curvature: 0.0453 1/m

Moment: 721 kN/m

Axial Force Capacity: 15329 kN,
Maximum Moment: 857 kN.m, Curvature: 0.0741 1/m
Yielding Curvature: 0.0044 1/m
Ultimate Curvature: 0.0453 1/m
Ductility: 10.3

Figure 14: A screenshot of the moment curvature curve.



Curvature values at cetain material strains

○ Peak Strain of plain conctrete under compression
○ Ultimate Strain of plain conctrete under compression (ULTIMATE CURVATURE)
○ Peak Strain of confined conctrete under compression
○ Ultimate Strain of confined conctrete under compression
○ Peak Strain of concrete under tension
○ Ultimate Strain of concrete under tension
○ Yield Strain of steel bars (YIELDING CURVATURE)
○ Ultimate Strain of steel bars
● MAXIMUM MOMENT RESISTANCE

Force [kN]	Bending Moment [kN.m]	μ [%]
0	723	0
766	930	5
1533	1133	10
2299	1298	15
3066	1435	20
3832	1536	25
4599	1527	30
5365	1503	35
6131	1470	40
6898	1419	45
7664	1345	50
8431	1245	55
9197	1115	60

Applied Force: 0 kN

Moment Resistance: 723 kN/m

Figure 15: A screenshot of the interaction curve.

This program was designed for educational purpose to study the effects of several factors on moment curvature, interaction curve and curvature ductility. Several sections with various dimensions and material properties will be compared in this thesis. The used cross sections are listed in table 3, reinforcement distribution in table 4, and material properties in table5.

Table 3: Sections Dimensions.

	Height	Width	Concrete Cover	Height / Width
Section 1	500	300	20	1.67
Section 2	800	500	20	1.60
Section 3	1200	600	20	2.00
Wall Section	3000	300	20	10

Table 4: Sections Reinforcement.

	Stirrups		Top reinforcement		Bottom reinforcement		Middle reinforcement	
	Diameter	Spacing	Diameter	Number	Diameter	Number	Diameter	Number
Section 1	8	100	16	3	16	3	16	2
Section 2	8	80	20	3	20	5	12	2
Section 3	10	80	25	4	25	2×4	12	2×2
Wall	8	100	20	4×2	20	4×2	12	10×2

Table 5: Material Properties.

	Concrete				Steel			
	f_{cm}	ε_{cm}	ε_{cu}	E_c	f_y	f_u	E_s	f_{yt}
Low Strength	15	0.002	0.004	18319	280	420	200000	280
Normal Strength	35	0.002	0.0032	27983	520	690	200000	280
High Strength	80	0.0024	0.0026	42306	690	760	200000	420

The Moment Curvature curves of MCI software were compared with Xtract software and showed a good agreement as in Figure 16, Figure 18, Figure 20, Figure 22, Figure 24, Figure 26, Figure 28, Figure 30, Figure 32, Figure 34, Figure 36, and Figure 38. A slight shift was noticed in some sections after yielding point, and the reason of this shift is because of each software uses different formulae for concrete stress strain relationship and a different shape of mesh. Interaction curves of section 1 with low, normal, and high strength materials were compared with both Xtract and ETABS software as shown in Figure 17, Figure 19, and Figure 21 and they showed a good agreement, where Eurocode 2-2004 [14] was the used code in ETABS for column design. On the other hand, since ETABS software provides interaction curve for column sections with uniformly distributed reinforcement, thus section 2, section 3, and wall section were only compared with Xtract and showed a good agreement as in Figure 23, Figure 25, Figure 27, Figure 29, Figure 31, Figure 33, Figure 35, Figure 37, and Figure 39.

CHAPTER 4

RESULTS AND DISCUSSIONS

5.1 MOMENT CURVATURE

As previously mentioned, MCI software was developed for estimating the curvature ductility through parametric study where different RC sections at different strength characteristics of concrete with and without the consideration of confinement, axial load, and tension in concrete was performed. Furthermore, the written code for MCI software is shown in Appendix II. The software plots the interaction curve and calculates the yielding curvature, ultimate curvature, and curvature ductility accurately. Accordingly, three various strength characteristics of concrete which are low, normal, and high strength concrete were used for conducting the parametric study as well as four different percentages of axial load of 0%, 20%, 40%, and 60% were selected. Thereafter, the results of section 1, 2,3, and wall section of MCI software were compared with Xtract and ETABS for validating the outcomes. However, only results of section 1 were compared with both ETABS and Xtract while results of the other sections were compared only with Xtract since ETABS software provides interaction curve for column sections with uniformly distributed reinforcement. As can be noticed from the results, the accuracy of MCI software is somewhat similar to Xtract and ETABS. In fact, the interaction curve increases with the increase in the strength of the material for all sections. However, the results of section 2 reflected the best accuracy of MCI in comparison to Xtract while the results of wall section relatively exhibited the lowest accuracy as illustrated in Figure 17, Figure 19, Figure 21, Figure 23, Figure 25, Figure 27, Figure 29, Figure 31, Figure 33, Figure 35, Figure 37, and Figure 39.

5.2 EFFECT OF AXIAL LOAD

In this section, the influence of the axial load is discussed in detail. Generally, the results of this study have shown that applying an axial load on a certain reinforced concrete section reduces its ductility as shown in Figure 16,Figure 18, and Figure 20, in which the ductility of section 1 has reduced by almost 80% for 20% axial load regardless of the considerable increase in the moment as compressive axial load reduces the tensile stresses on steel and delay yielding in main bars. Regarding low strength case, the increase in moment is associated with the increase in axial load from 0% to 40% where any increase in axial load results in increase in moment. Normal strength concrete case exhibited similar results where the axial load of 40% showed the highest values in terms of the moment except the case of 20% for section 2 which showed highest values. High strength case showed consistent results for all sections where the highest moment values were at 40%. On the contrary, the decrease in curvature is associated with the increase in axial load from 0% to 60% where any increase in axial load results in decrease in the curvature for all sections at all strength characteristic cases as illustrated in Figure 16, Figure 18, Figure 20, Figure 22, Figure 24, Figure 26, Figure 28, Figure 30, Figure 32, Figure 34, Figure 36, and Figure 38. This observation can mainly be attributed to the increase in compressive stresses on concrete and the decrease in tensile stresses on steel bars. Furthermore, it can be seen in Table 6, Table 7, Table 8, and Table 9 that the ductility of the section reaches its peak in the case of axially unloaded column. Whereas it reduces between 80% to 90% when an axial load of about 20% of the ultimate capacity is applied. On the other hand, when the applied axial load is below 40% of the capacity of the section bending moment increases moderately while higher axial loads results in reducing the bending capacity of the section.

5.3 EFFECT OF STRENGTH OF MATERIALS

In this section, the effect of selecting high strength materials on the load carrying capacity, moment capacity as well as the ductility will be discussed in detail. In general, the curvature ductility of a given reinforced concrete section is influenced by three main factors as discussed by Olivia and Mandal (2015) [2]. These factors are the variation in the loads acting on the section including the rate of axial load applied, the ratio of longitudinal and transverse reinforcements, and the elastic capacity of concrete and steel martials. Similar observation was discussed by Baji and Ronagh (2011) [15] in which they highlighted that the curvature ductility increases with respect to the section size in which larger section provides higher ductility as compared to small sections and increasing the concrete's compressive strength results in enhanced curvature ductility.

The yielding moment can be referred to the peak of moment-curvature curve of an element which is directly dependent on the strength of the materials where any increase in the strength of the concrete or reinforcements results in higher yielding moment. Regarding the load carrying capacity, it is provided by the element to produce the ultimate moment which is referred to the moment acting at the capacity (ultimate). The utilization of high strength materials leads to an increase in the load carrying capacity and hence the ultimate moment capacity. As can be seen from the results, the increase in the strength of the material is accompanied with significant increase in the moment for all sections. For example, the maximum magnitude of moment for wall section at low strength case was approximately 7400 $\frac{\mathrm{kN}}{\mathrm{M}}$while it was 14000 $\frac{\mathrm{kN}}{\mathrm{M}}$for normal strength and 25000 $\frac{\mathrm{kN}}{\mathrm{M}}$ for high strength case. On the other hand, ductility can be described as the ability of element to maintain plastic deformation to a high degree under the effect of tensile load before reaching fracture or failure. In addition to that, ductility can be represented as the permanent deformation using stress-strain curve. Therefore, as the strength of the materials increases, the difference between the moment capacity and ultimate moment increases and hence notably reducing the ductility of the material. With respect to the curvature, the increase in the strength of the material is associated with considerable reduction in the ductility for all sections. For example, the maximum magnitude of curvature for wall section at low strength case was approximately 0.0048 $\frac{1}{M}$ while it was 0.003 $\frac{1}{M}$ for normal strength and 0.0022 $\frac{1}{M}$ for high strength case.

In general, the results of this study have shown that when the tensile strength of concrete was included into analysis, an increment in moment resistance was observed for low curvature values, then a sudden decrease in resistance and returns to the same values in the case of neglecting tension in concrete. Moreover, considering the resistance of the section is the maximum resistance when tensile effect is included may causes a sudden collapse. Therefore, it is preferable to neglect tension in design. Where curvature ductility was not significantly affected, with a slight increase in the yielding curvature value, which led to a slight decrease in the curvature ductility.

The effect of lateral confinement on moment resistance and ductility was neglectable before the point at which concrete begins to collapse on compression. After this point, it was noticed a delay in total collapse and confinement causes an increase in moment resistance in some cases. Therefore, a good confinement helps delay the total section collapse, but should not be included during design.

By adding axial force gradually, we get the interaction curve for the three sections and it was noticed a gradual increase in the moment capacity of the section when applying a small axial force that does not exceed 30 to 40 percent of the total axial resistance, then moment capacity begins decreasing until the section loses its moment resistance when axial force equals to the maximum axial resistance. Where curvature ductility gradually decreases with the addition of axial force until it reaches a value of one, where the collapse under moment after this point becomes brittle.

Table 6: The curvature ductility of section 1 calculated by MCI software.

		Neglecting Confinement and Tension in Concrete			With Tension			With Confinement		
		$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$	$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$	$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$
LS	0.0	0.0042	0.0780	**18.6**	0.0046	0.0769	**16.7**	0.0042	0.0782	**18.6**
	0.2	0.0059	0.0210	**3.6**	0.0063	0.0205	**3.3**	0.0059	0.0245	**4.2**
	0.4	0.0048	0.0133	**2.8**	0.0044	0.0128	**2.9**	0.0050	0.0158	**3.2**
	0.6	0.0031	0.0098	**3.2**	0.0031	0.0095	**3.1**	0.0033	0.0115	**3.5**
NS	0.0	0.0074	0.0556	**7.5**	0.0077	0.0542	**7.0**	0.0074	0.0555	**7.5**
	0.2	0.0101	0.0177	**1.8**	0.0103	0.0171	**1.7**	0.0101	0.0182	**1.8**
	0.4	0.0096	0.0104	**1.1**	0.0092	0.0101	**1.1**	0.0100	0.0110	**1.1**
	0.6	0.0064	0.0072	**1.1**	0.0063	0.0072	**1.1**	0.0067	0.0079	**1.2**
HS	0.0	0.0093	0.0564	**6.1**	0.0096	0.0548	**5.7**	0.0093	0.0563	**6.1**
	0.2	0.0146	0.0130	**0.9**	0.0142	0.0126	**0.9**	0.0145	0.0128	**0.9**
	0.4	0.0078	0.0074	**0.9**	0.0078	0.0072	**0.9**	0.0118	0.0072	**0.6**
	0.6	0.0047	0.0047	**1.0**	0.0047	0.0047	**1.0**	0.0080	0.0048	**0.6**

Table 7: The curvature ductility of section 2 calculated by MCI software.

		Neglecting Confinement and Tension in Concrete			With Tension			With Confinement		
		$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$	$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$	$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$
LS	0.0	0.0025	0.0648	**25.9**	0.0029	0.0618	**21.3**	0.0025	0.0647	**25.9**
	0.2	0.0036	0.0141	**3.9**	0.0039	0.0132	**3.4**	0.0036	0.0171	**4.8**
	0.4	0.0027	0.0080	**3.0**	0.0026	0.0075	**2.9**	0.0028	0.0100	**3.6**
	0.6	0.0019	0.0059	**3.1**	0.0019	0.0058	**3.1**	0.0019	0.0071	**3.7**
NS	0.0	0.0044	0.0479	**10.9**	0.0047	0.0462	**9.8**	0.0044	0.0477	**10.8**
	0.2	0.0061	0.0111	**1.8**	0.0063	0.0105	**1.7**	0.0061	0.0119	**2.0**

	0.4	0.0056	0.0063	**1.1**	0.0054	0.0061	**1.1**	0.0059	0.0069	**1.2**
	0.6	0.0038	0.0044	**1.2**	0.0038	0.0044	**1.2**	0.0039	0.0048	**1.2**
HS	0.0	0.0056	0.0512	**9.1**	0.0058	0.0491	**8.5**	0.0056	0.0512	**9.1**
	0.2	0.0079	0.0082	**1.0**	0.0083	0.0078	**0.9**	0.0085	0.0080	**0.9**
	0.4	0.0047	0.0046	**1.0**	0.0047	0.0045	**1.0**	0.0072	0.0045	**0.6**
	0.6	0.0029	0.0029	**1.0**	0.0029	0.0029	**1.0**	0.0050	0.0030	**0.6**

Table 8: The curvature ductility of section 3 calculated by MCI software.

		Neglecting Confinement and Tension in Concrete			With Tension			With Confinement		
		$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$	$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$	$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$
LS	0.0	0.0018	0.0661	**36.7**	0.0020	0.0651	**32.6**	0.0018	0.0661	**36.7**
	0.2	0.0026	0.0105	**4.0**	0.0028	0.0100	**3.6**	0.0026	0.0131	**5.0**
	0.4	0.0018	0.0055	**3.1**	0.0017	0.0052	**3.1**	0.0019	0.0072	**3.8**
	0.6	0.0012	0.0040	**3.3**	0.0012	0.0039	**3.3**	0.0013	0.0050	**3.8**
NS	0.0	0.0031	0.0462	**14.9**	0.0033	0.0451	**13.7**	0.0031	0.0461	**14.9**
	0.2	0.0044	0.0080	**1.8**	0.0045	0.0077	**1.7**	0.0044	0.0088	**2.0**
	0.4	0.0038	0.0043	**1.1**	0.0036	0.0042	**1.2**	0.0040	0.0048	**1.2**
	0.6	0.0025	0.0029	**1.2**	0.0025	0.0029	**1.2**	0.0026	0.0034	**1.3**
HS	0.0	0.0039	0.0473	**12.1**	0.0041	0.0458	**11.2**	0.0039	0.0472	**12.1**
	0.2	0.0061	0.0057	**0.9**	0.0059	0.0055	**0.9**	0.0061	0.0056	**0.9**
	0.4	0.0031	0.0031	**1.0**	0.0031	0.0030	**1.0**	0.0049	0.0030	**0.6**
	0.6	0.0017	0.0017	**1.0**	0.0018	0.0018	**1.0**	0.0033	0.0020	**0.6**

Table 9: The curvature ductility of wall section calculated by MCI software.

		Neglecting Confinement and Tension in Concrete			With Tension			With Confinement		

		$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$	$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$	$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$
LS	0.0	0.0007	0.0109	**15.6**	0.0007	0.0106	**15.1**	0.0007	0.0119	**17.0**
	0.2	0.0009	0.0040	**4.4**	0.0010	0.0038	**3.8**	0.0009	0.0046	**5.1**
	0.4	0.0007	0.0023	**3.3**	0.0007	0.0019	**2.7**	0.0007	0.0022	**3.1**
	0.6	0.0005	0.0017	**3.4**	0.0005	0.0016	**3.2**	0.0005	0.0019	**3.8**
NS	0.0	0.0011	0.0098	**8.9**	0.0012	0.0095	**7.9**	0.0011	0.0101	**9.2**
	0.2	0.0016	0.0031	**1.9**	0.0016	0.0029	**1.8**	0.0016	0.0033	**2.1**
	0.4	0.0015	0.0018	**1.2**	0.0014	0.0017	**1.2**	0.0015	0.0019	**1.3**
	0.6	0.0010	0.0012	**1.2**	0.0010	0.0012	**1.2**	0.0011	0.0014	**1.3**
HS	0.0	0.0014	0.0105	**7.5**	0.0015	0.0102	**6.8**	0.0014	0.0104	**7.4**
	0.2	0.0020	0.0023	**1.2**	0.0021	0.0022	**1.0**	0.0020	0.0023	**1.2**
	0.4	0.0012	0.0012	**1.0**	0.0013	0.0012	**0.9**	0.0019	0.0013	**0.7**
	0.6	0.0007	0.0007	**1.0**	0.0007	0.0007	**1.0**	0.0013	0.0009	**0.7**

5.4 PROPOSED DUCTILITY EQUATIONS

As mentioned earlier, curvature ductility is important for design. To calculate ductility, ultimate curvature is divided by yielding curvature. After analyzing several sections with various properties using the program that was designed for this purpose the equations shown in the following table were proposed:

Table 10: Curvature ductility equations for rectangular and wall sections.

For Rectangular Sections	
$\propto_1 = \dfrac{f_y}{E_s \cdot d}$ $\propto_2 = \dfrac{N + f_y \cdot A_s}{B \cdot d^2 \cdot E_c} + \propto_1$	$\propto_3 = \dfrac{\varepsilon_{cu} \cdot f_{cm} \cdot B}{16 \cdot A'_s \cdot 10^6}$ $\propto_4 = \dfrac{N + f_y \cdot (A_s + A''_s)}{16 \cdot A'_s \cdot 10^6} - \dfrac{\varepsilon_{cu}}{80}$
$\emptyset_y = \sqrt{\propto_2^2 - \propto_1^2} + \propto_2$	$\emptyset_u = \sqrt{\propto_4^2 + \propto_3} - \propto_4$
$\eta_\emptyset = \dfrac{\emptyset_u}{\emptyset_y} \geq 1$	

For Wall Sections	
$\propto_1 = \dfrac{f_y}{E_s \cdot d}$ $\propto_2 = \dfrac{N + f_y \cdot A_s}{B \cdot d^2 \cdot E_c} + \propto_1$	$\propto_3 = \dfrac{5 \cdot \varepsilon_{cu} \cdot f_{cm} \cdot B}{H_C \cdot A_s' \cdot 10^6}$ $\propto_4 = \dfrac{N + f_y \cdot (A_s + A_s'')}{2 \cdot H_C \cdot A_s' \cdot 10^6} - \dfrac{\varepsilon_{cu}}{H_C}$
$\emptyset_y = \sqrt{\propto_2^2 - \propto_1^2} + \propto_2$	$\emptyset_u = \sqrt{\propto_4^2 + \propto_3} - \propto_4$
$\eta_\emptyset = \dfrac{\emptyset_u}{\emptyset_y} \geq 1$	

5.5 PROPOSED DUCTILITY EQUATIONS VS SOFTWARE RESULTS

The proposed equation for estimating the ductility yielded similar results to MCI software with a mean error of ± 15% in the case of absence of axial force and a mean error of ± 22% in the case that axial force is available as shown in Tables 11 & 12 and Figures 48, 49, 50 & 51.

In fact, the yield curvature of reinforced concrete section can be affected by the dimensions of its cross-section, the rate of the applied axial load, the characteristic strength of concrete, and slightly by the thickness of the concrete cover and the amount of longitudinal reinforcement according to Sheikh et al. (2010) [16].

Table 11: Comparison of curvature ductility between MCI software and the proposed equation without axial force.

$\mu = 0$									
	MCI Software			Proposed Equation			Error %		
	$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$	$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$	$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$
#1-LS	0.0042	0.0780	**18.6**	0.0041	0.0769	**18.8**	-2 %	-1 %	**1 %**
#1-NS	0.0074	0.0556	**7.5**	0.0072	0.0584	**8.1**	-3 %	5 %	**8 %**
#1-HS	0.0093	0.0564	**6.1**	0.0091	0.0653	**7.2**	-2 %	16 %	**18 %**
#2-LS	0.0025	0.0648	**25.9**	0.0025	0.0729	**29.4**	0 %	13 %	**14 %**
#2-NS	0.0044	0.0479	**10.9**	0.0043	0.0547	**12.6**	-2 %	14 %	**16 %**

#2-HS	0.0056	0.0512	**9.1**	0.0055	0.0621	**11.3**	-2 %	21 %	**24 %**
#3-LS	0.0018	0.0661	**36.7**	0.0017	0.0532	**31.0**	-6 %	-20 %	**-16 %**
#3-NS	0.0031	0.0462	**14.9**	0.0030	0.0321	**10.8**	-3 %	-31 %	**-28 %**
#3-HS	0.0039	0.0473	**12.1**	0.0038	0.0355	**9.5**	-3 %	-25 %	**-21 %**
W-LS	0.0007	0.0109	**15.6**	0.0006	0.0112	**18.5**	-14 %	3 %	**19 %**
W-NS	0.0011	0.0098	**8.9**	0.0011	0.0084	**7.9**	0 %	-14 %	**-11 %**
W-HS	0.0014	0.0105	**7.5**	0.0014	0.0096	**7.0**	0 %	-9 %	**-7 %**

Table 12: Comparison of curvature ductility between MCI software and the proposed equation with 20% axial force.

$\mu = 0.2$									
	MCI Software			Proposed Equation			Error %		
	$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$	$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$	$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$
#1-LS	0.0059	0.0210	**3.6**	0.0056	0.0279	**5.0**	-5 %	33 %	**39 %**
#1-NS	0.0101	0.0177	**1.8**	0.0096	0.0171	**1.8**	-5 %	-3 %	**0 %**
#1-HS	0.0130	0.0130	**1.0**	0.0127	0.0149	**1.2**	-2 %	15 %	**20 %**
#2-LS	0.0036	0.0141	**3.9**	0.0033	0.0178	**5.3**	-8 %	26 %	**36 %**
#2-NS	0.0061	0.0111	**1.8**	0.0058	0.0117	**2.0**	-5 %	5 %	**11 %**
#2-HS	0.0079	0.0082	**1.0**	0.0076	0.0100	**1.3**	-4 %	22 %	**30 %**
#3-LS	0.0026	0.0105	**4.0**	0.0023	0.0112	**5.0**	-12 %	7 %	**25 %**
#3-NS	0.0044	0.0080	**1.8**	0.0039	0.0072	**1.9**	-11 %	-10 %	**6 %**
#3-HS	0.0057	0.0057	**1.0**	0.0051	0.0063	**1.2**	-11 %	11 %	**20 %**
W-LS	0.0009	0.0040	**4.4**	0.0009	0.0032	**3.4**	0 %	-20 %	**-23 %**
W-NS	0.0016	0.0031	**1.9**	0.0016	0.0021	**1.3**	0 %	-32 %	**-32 %**
W-HS	0.0020	0.0023	**1.2**	0.0021	0.0018	**1.0**	5 %	-22 %	**-17 %**

5.6 OLIVIA`S EQUATION FOR DUCTILITY VS SOFTWARE RESULTS

In fact, a detailed comparison between the developed software herein and the approach suggested by Olivia & Mandal (2015) [2] has been conducted to evaluate the reliability of the proposed mathematical formulae. Generally, the results have shown a variation between both methodologies with an error of 56% and 126% for section 1 and 2 as well as the wall section respectively in the case of close values of tensile and compression reinforcements. These considerable differences can be mainly attributed to the basic assumption of these methods in which Olivia & Mandal assume that the compression reinforcements reach their yielding capacity before the crushing. This assumption cannot be generalized for all cases since it is applicable only when the ratio of compression reinforcements steel is relatively small as compared to the ratio of tensile reinforcements as seen in section 3 where the error was between 7% and 37% as shown in Table 13 and Figures 48, 49, 50 & 51. On the other hand, Olivia & Mandal's model cannot predict the cases of axially loaded sections.

Table 13: Comparison of curvature ductility between MCI software and Olivia & Mandal's equation without axial force.

$\mu = 0$									
	MCI Software			Olivia & Mandal Equation			Error %		
	$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$	$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$	$\emptyset_y$	$\emptyset_u$	$\eta_\emptyset$
#1-LS	0.0042	0.0780	**18.6**	0.0040	0.1155	**29.1**	-5 %	48 %	**56 %**
#1-NS	0.0074	0.0556	**7.5**	0.0070	0.1094	**15.5**	-5 %	97 %	**107 %**
#1-HS	0.0093	0.0564	**6.1**	0.0090	0.1243	**13.8**	-3 %	120 %	**126 %**
#2-LS	0.0025	0.0648	**25.9**	0.0024	0.0906	**37.4**	-4 %	40 %	**44 %**
#2-NS	0.0044	0.0479	**10.9**	0.0043	0.0858	**20.0**	-2 %	79 %	**83 %**
#2-HS	0.0056	0.0512	**9.1**	0.0055	0.0975	**17.8**	-2 %	90 %	**96 %**
#3-LS	0.0018	0.0661	**36.7**	0.0017	0.0385	**23.1**	-6 %	-42 %	**-37 %**

#3-NS	0.0031	0.0462	**14.9**	0.0029	0.0364	**12.4**	-6 %	-21 %	**-17 %**
#3-HS	0.0039	0.0473	**12.1**	0.0037	0.0414	**11.2**	-5 %	-12 %	**-7 %**
W-LS	0.0007	0.0109	**15.6**	0.0006	0.0205	**34.5**	-14 %	88 %	**121 %**
W-NS	0.0011	0.0098	**8.9**	0.0011	0.0194	**18.3**	0 %	98 %	**106 %**
W-HS	0.0014	0.0105	**7.5**	0.0014	0.0221	**16.2**	0 %	110 %	**116 %**

CHAPTER 5

CONCLUSIONS

This thesis has focused on estimating the curvature ductility of different RC sections at different strength characteristics of concrete with and without the application of axial load, confinement, and tension in concrete using a developed software and a proposed equation. As a part of the research, a parametric study was conducted to evaluate the influencing parameters on the curvature ductility of different RC sections.

In general, the developed software aimed to determine the moment curvature, interaction curve, and curvature ductility of rectangular RC sections and shear walls. The importance of this software is attributed to its enhanced features and capabilities in terms of the possibility of comparing different sections together, assessing the effect of axial load value on the section properties, considering the effects of confinement, and concrete's tensile strength as well as simply defining the material properties of the section either in a manual way or through a code-based equation. In addition to that, it automatically highlights the crucial points of a given curve in which the material achieved its ultimate capacity or has failed. Moreover, it is based on a sophisticated approach by means of conducting the analysis in the post-crush behavior through analyzing the section beyond the state of collapse of the upper layers of the concrete.

The results of this study have shown a significant improvement in the proposed approach against the currently available ones. Furthermore, the developed program was capable of analyzing and estimating the moment curvature, interaction curve, and curvature ductility of different RC sections with good accuracy in comparison to both ETABS and Xtract. In fact, the results of the parametric study have presented a considerable independency of the sectional ductility on the level of confinement and the tensile strength of the used concrete. Regarding the developed mathematical formulae, the ductility equation produced a good accuracy and has a good agreement with Olivia & Mandal`s equation except in the case of high compression reinforcement ratio where some notable differences were seen since Olivia & Mandal`s equation presumes that the compression reinforcement always reaches the yielding point before crushing. This study is expected to help practicing engineers in their daily works through reliably estimating the behavior of reinforced concrete section.

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APPENDIX I: LIST OF FIGURES

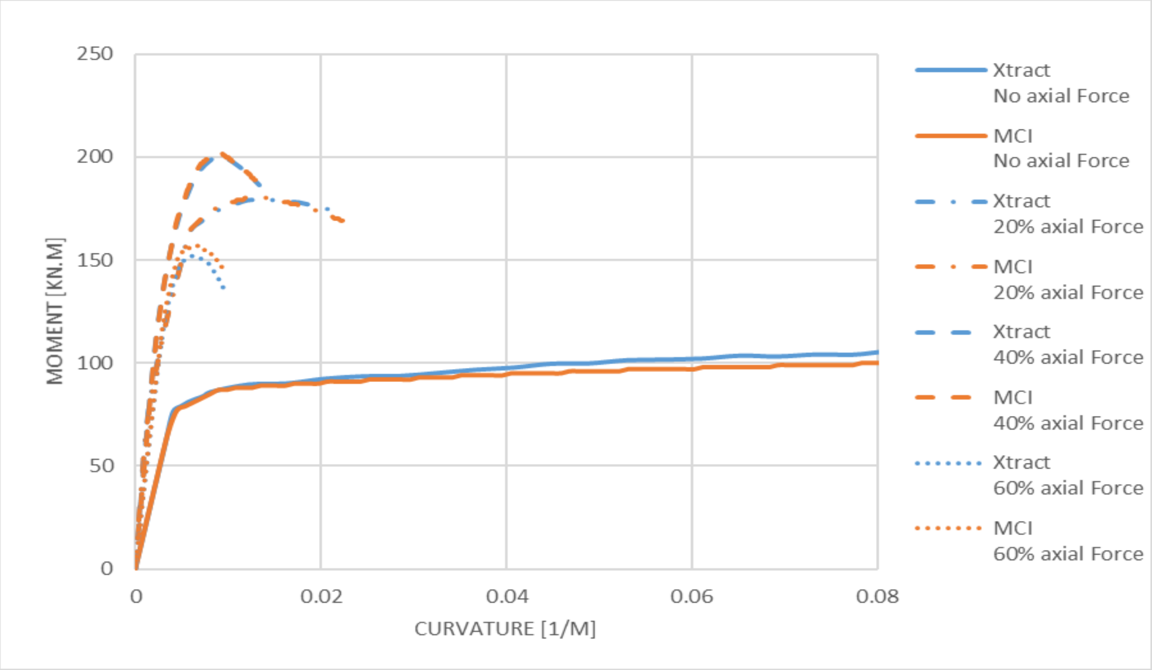


Figure 16:Moment Curvature Curves of Section 1 – Low Strength Materials

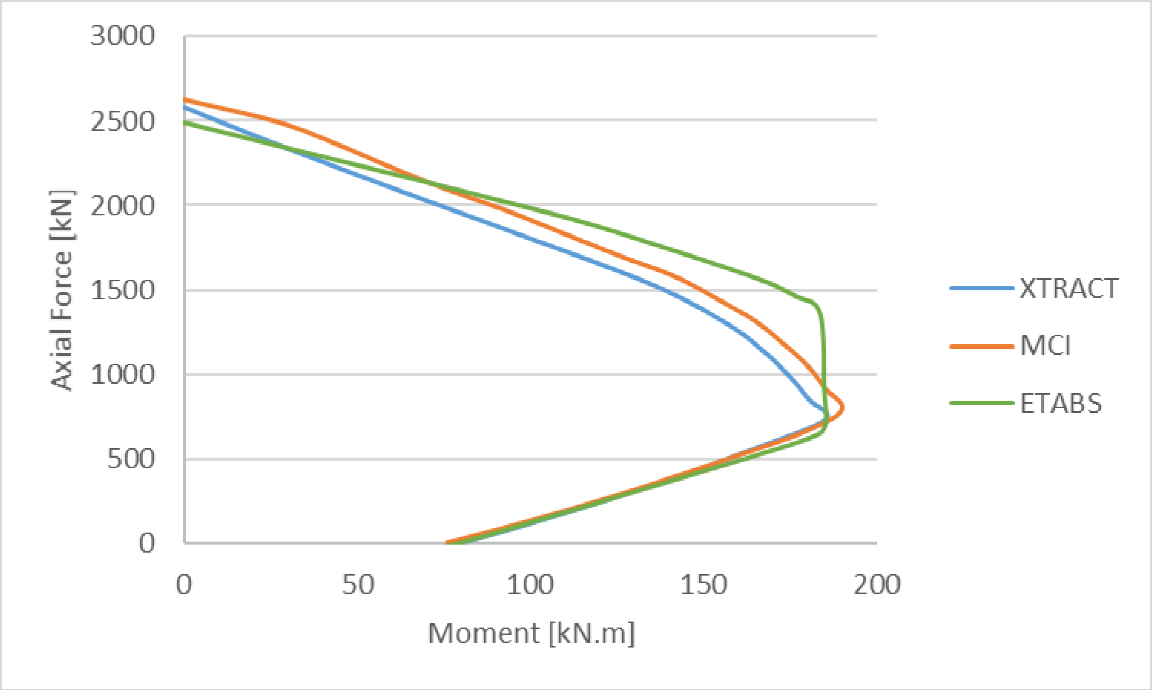


Figure 17:Interaction Curve of Section 1 – Low Strength Materials

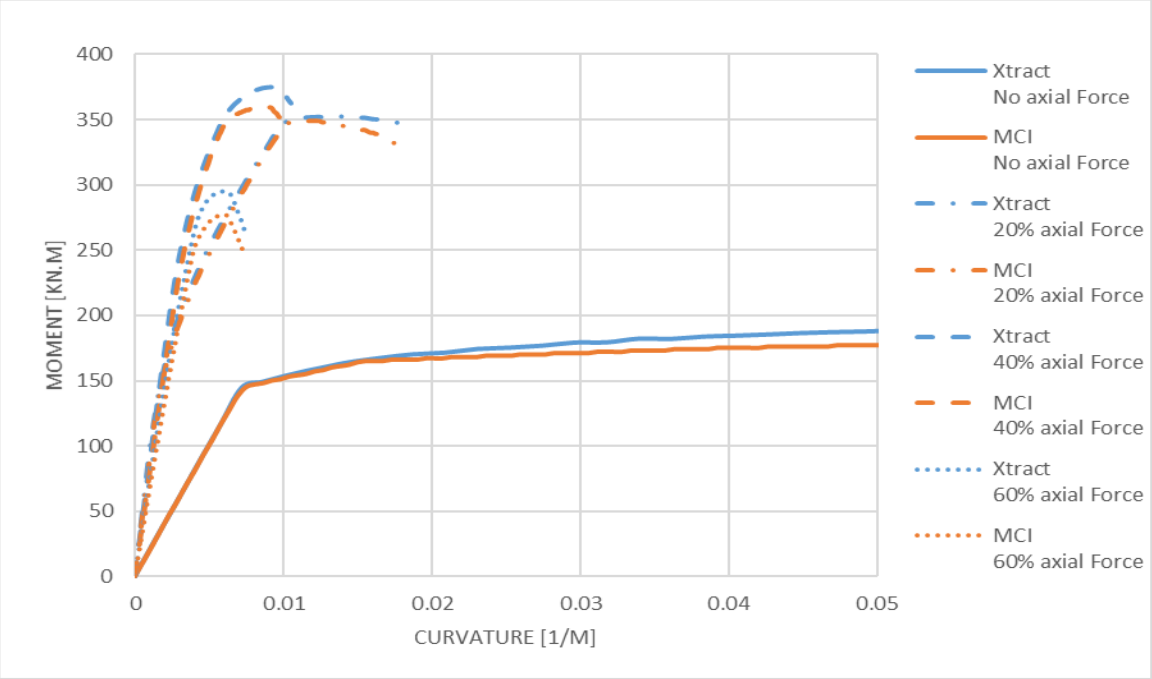


Figure 18:Moment Curvature Curves of Section 1 – Normal Strength Materials

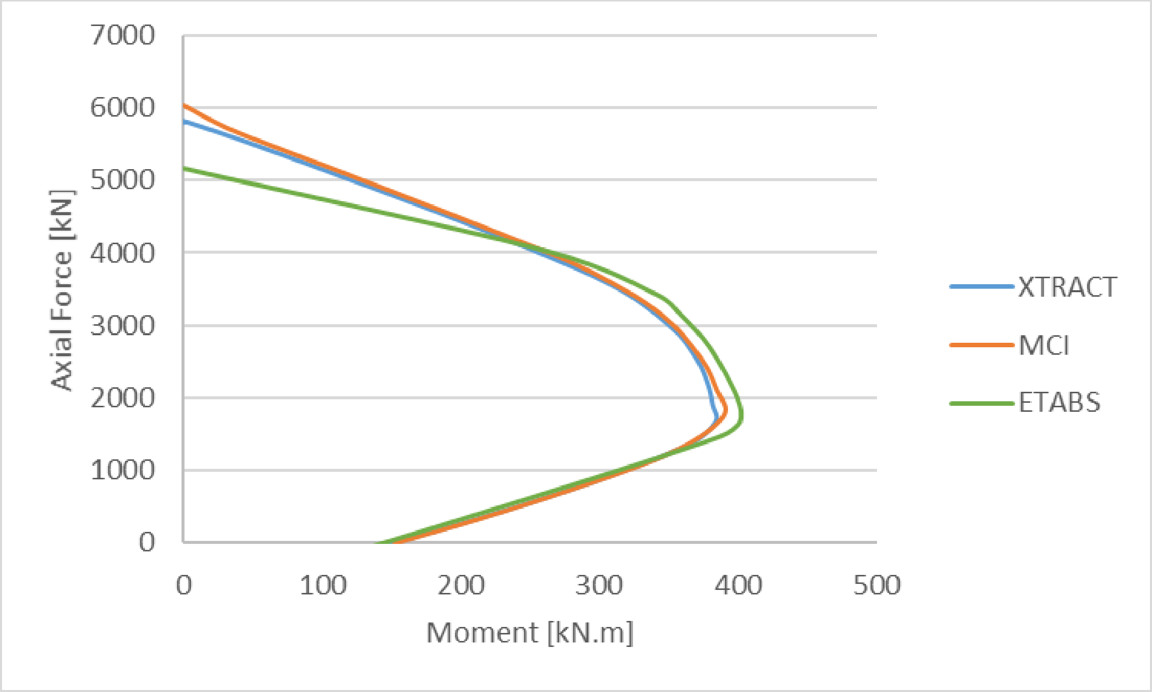


Figure 19:Interaction Curve of Section 1 – Normal Strength Materials

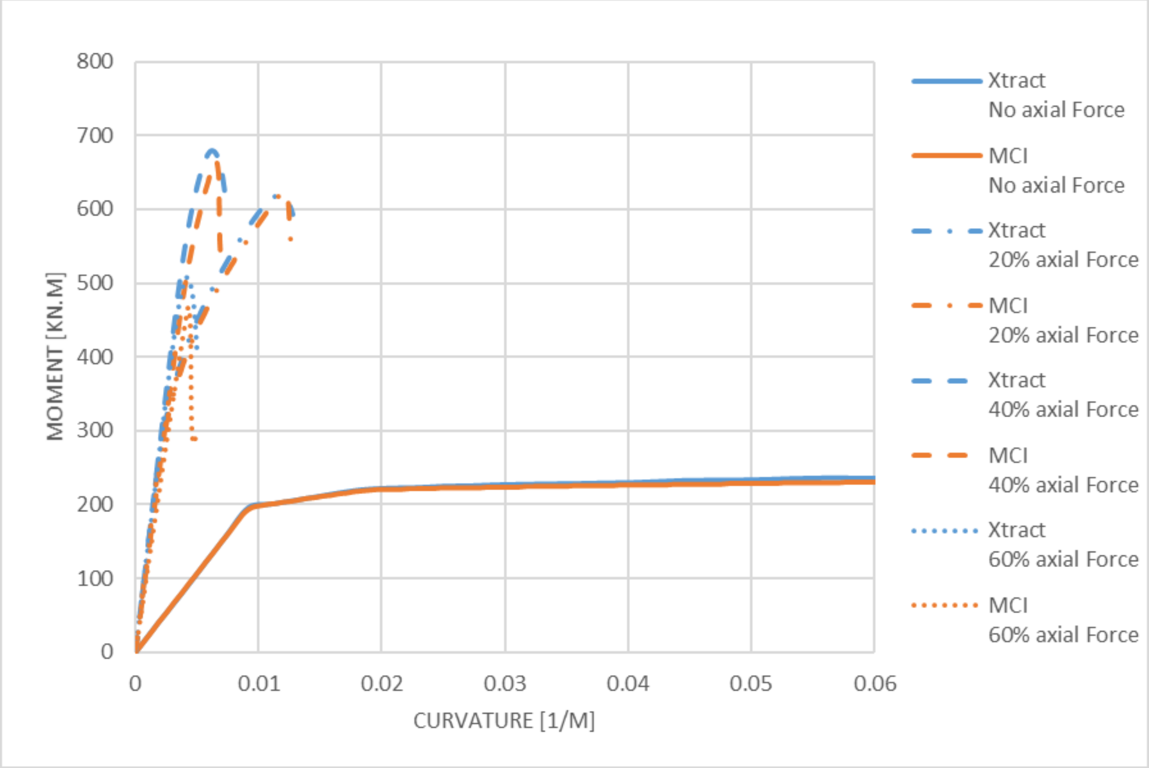


Figure 20:Moment Curvature Curves of Section 1 – High Strength Materials

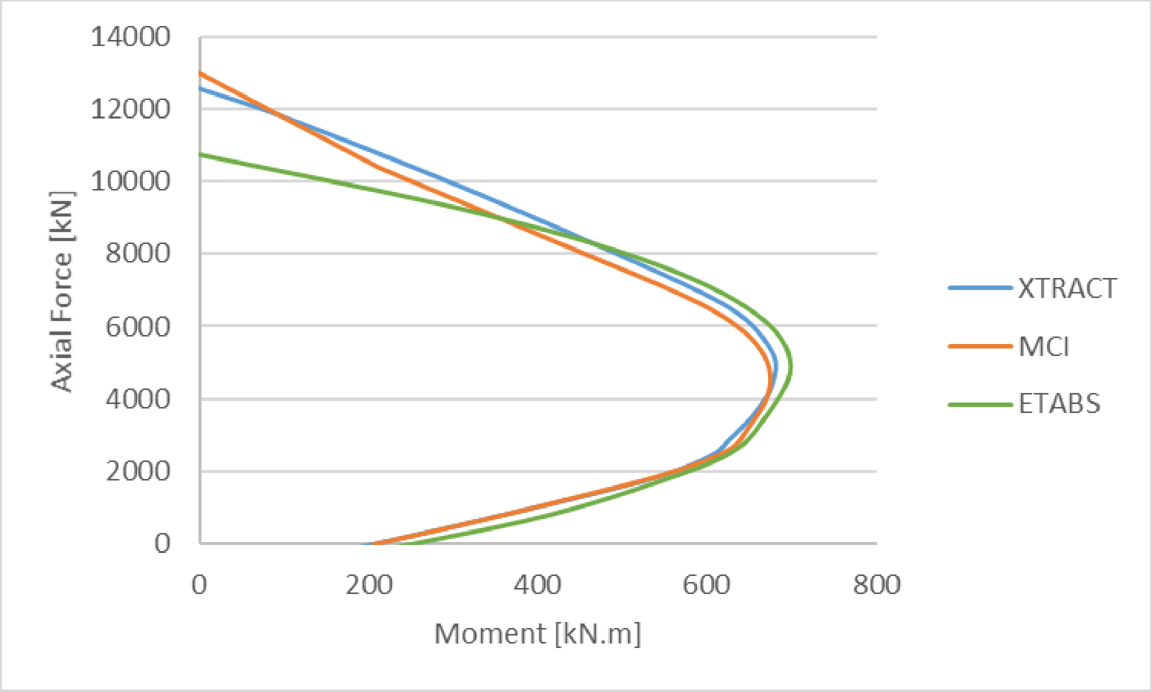


Figure 21:Interaction Curve of Section 1 – High Strength Materials

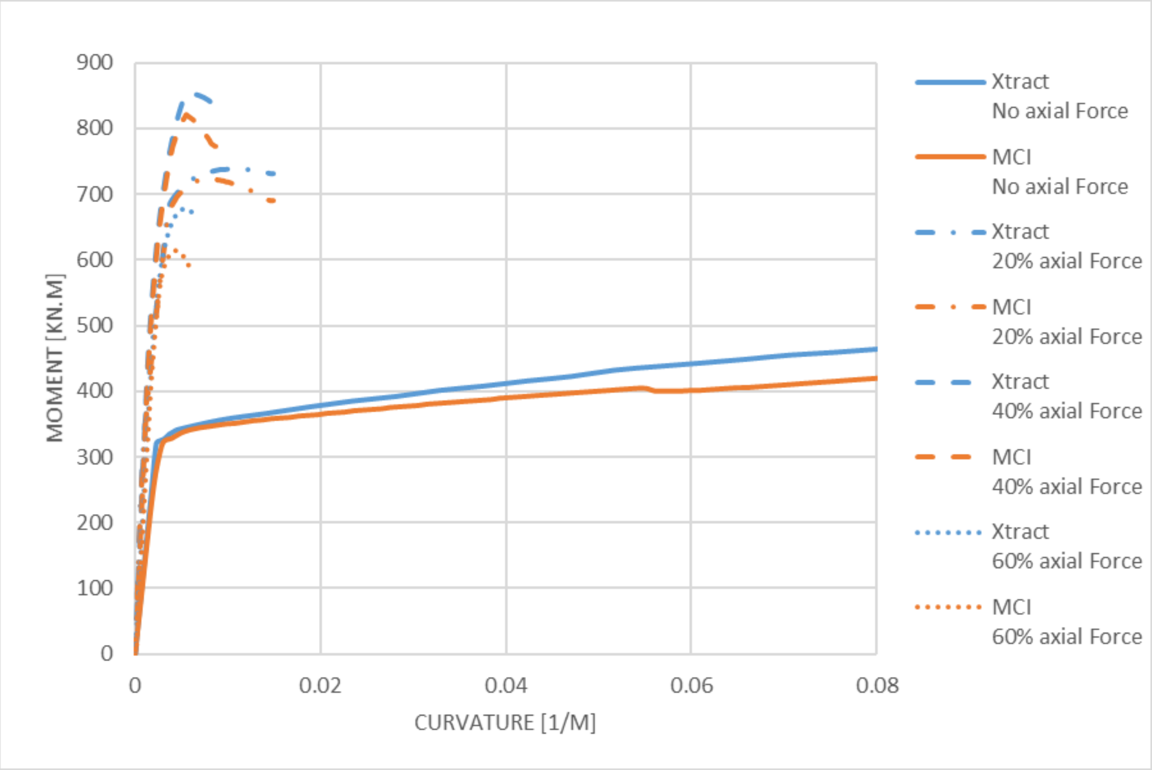


Figure 22:Moment Curvature Curves of Section 2 – Low Strength Materials

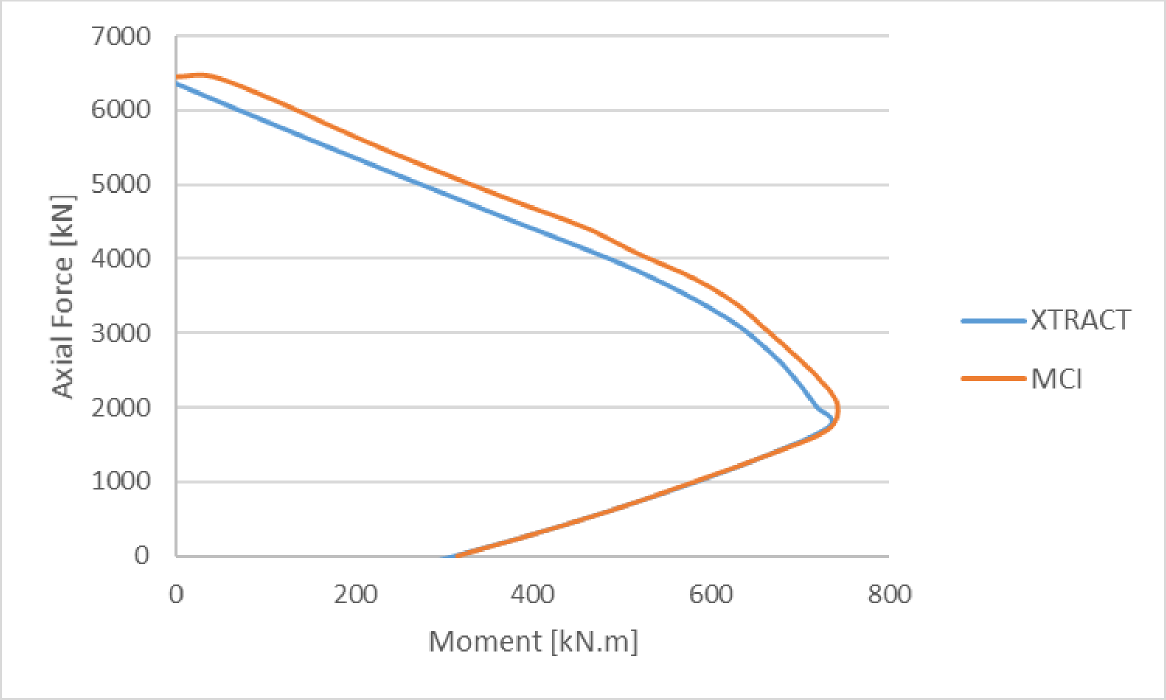


Figure 23:Interaction Curve of Section 2 – Low Strength Materials

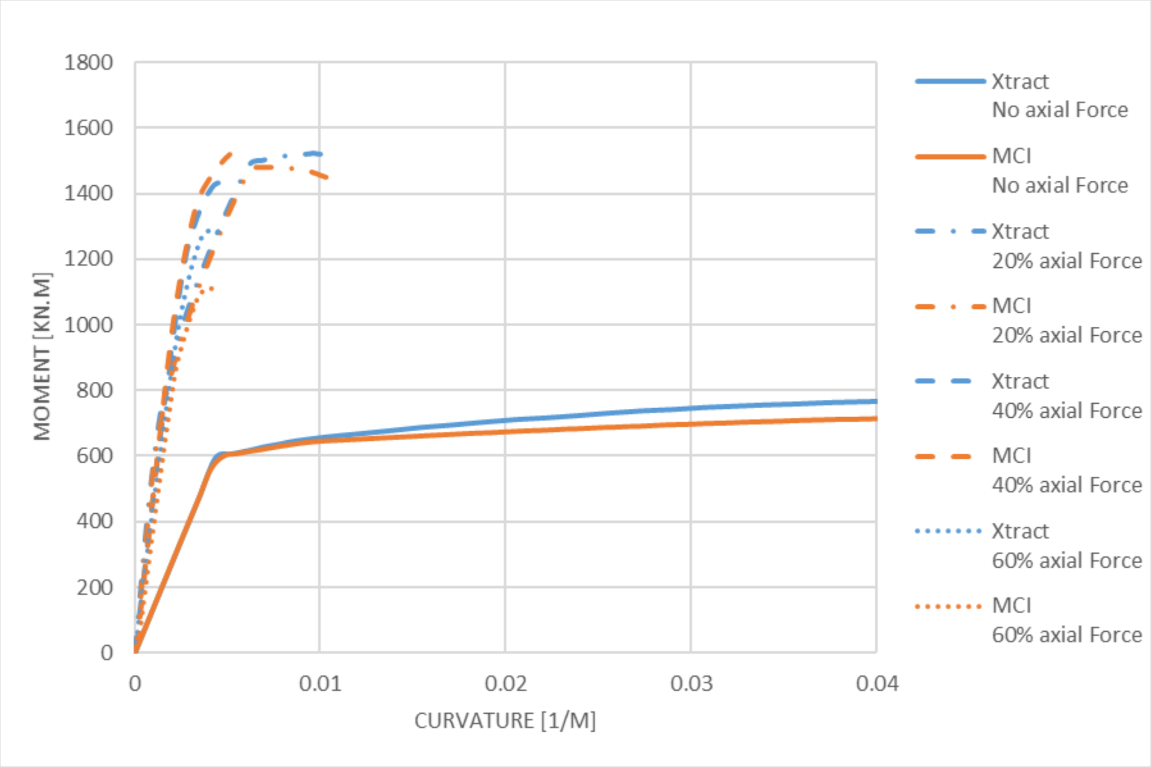


Figure 24:Moment Curvature Curves of Section 2 – Normal Strength Materials

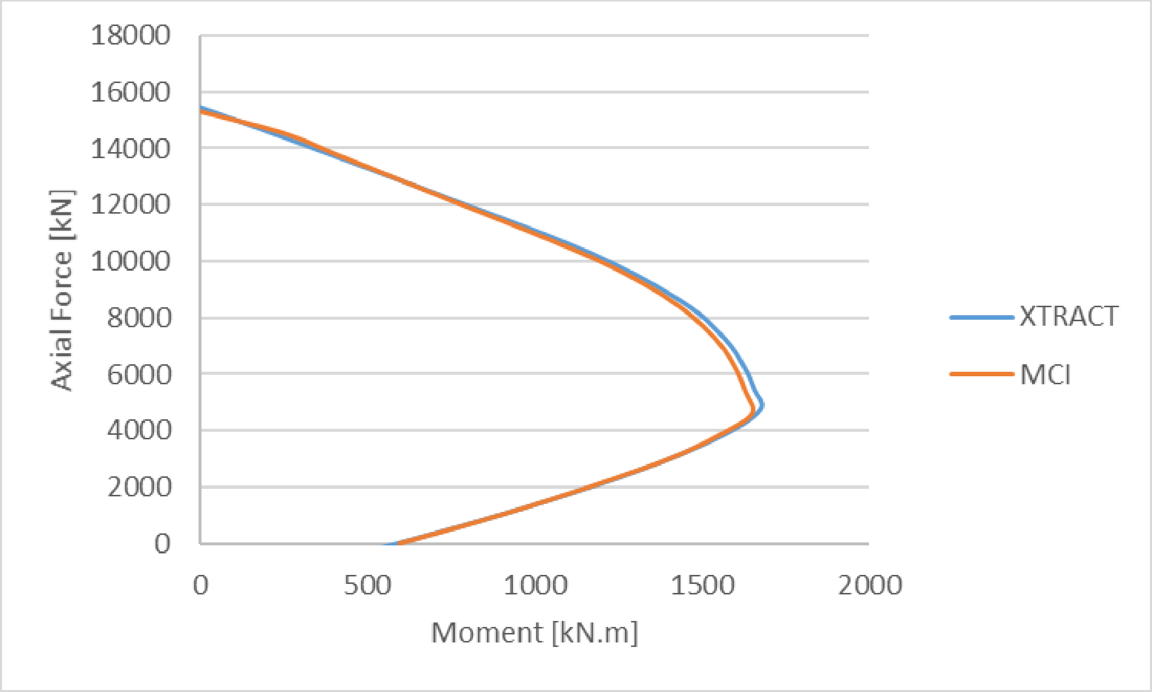


Figure 25:Interaction Curve of Section 2 – Normal Strength Materials

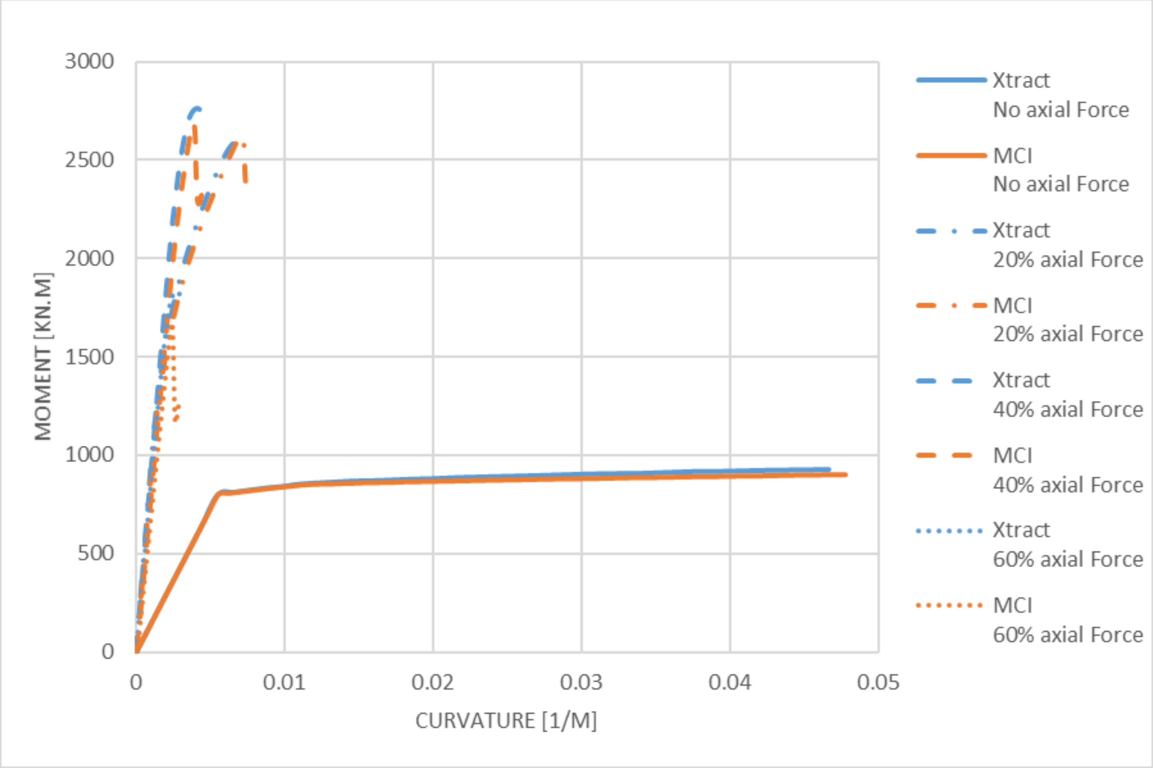


Figure 26:Moment Curvature Curves of Section 2 – High Strength Materials

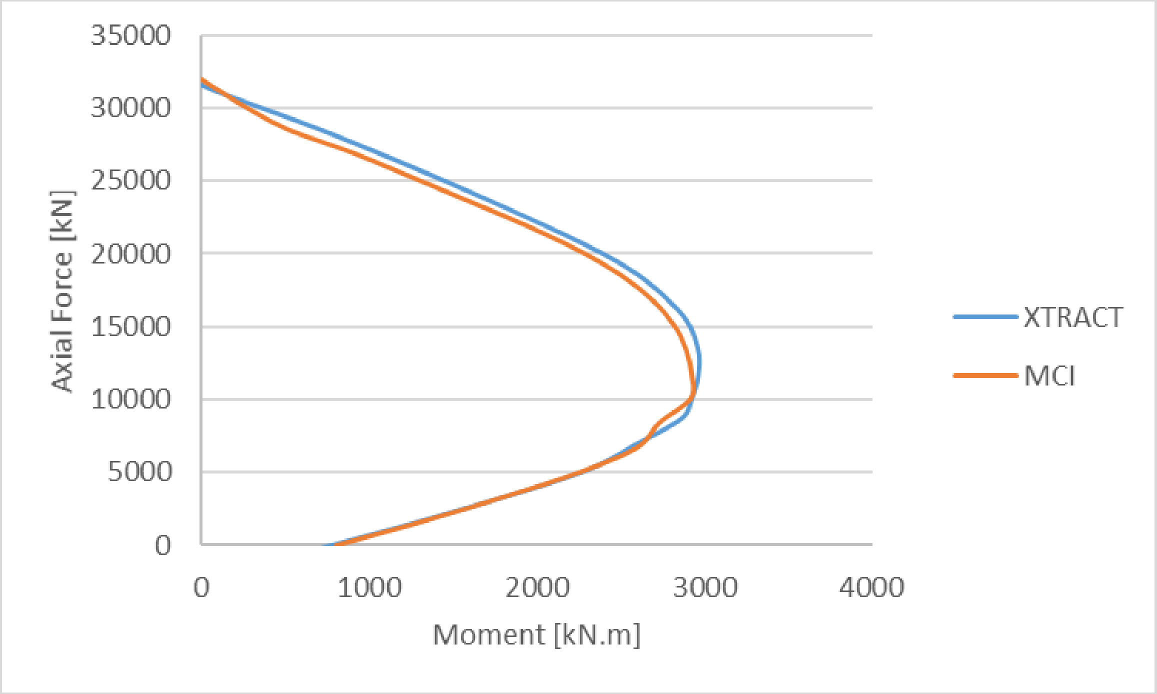


Figure 27:Interaction Curve of Section 2 – High Strength Materials

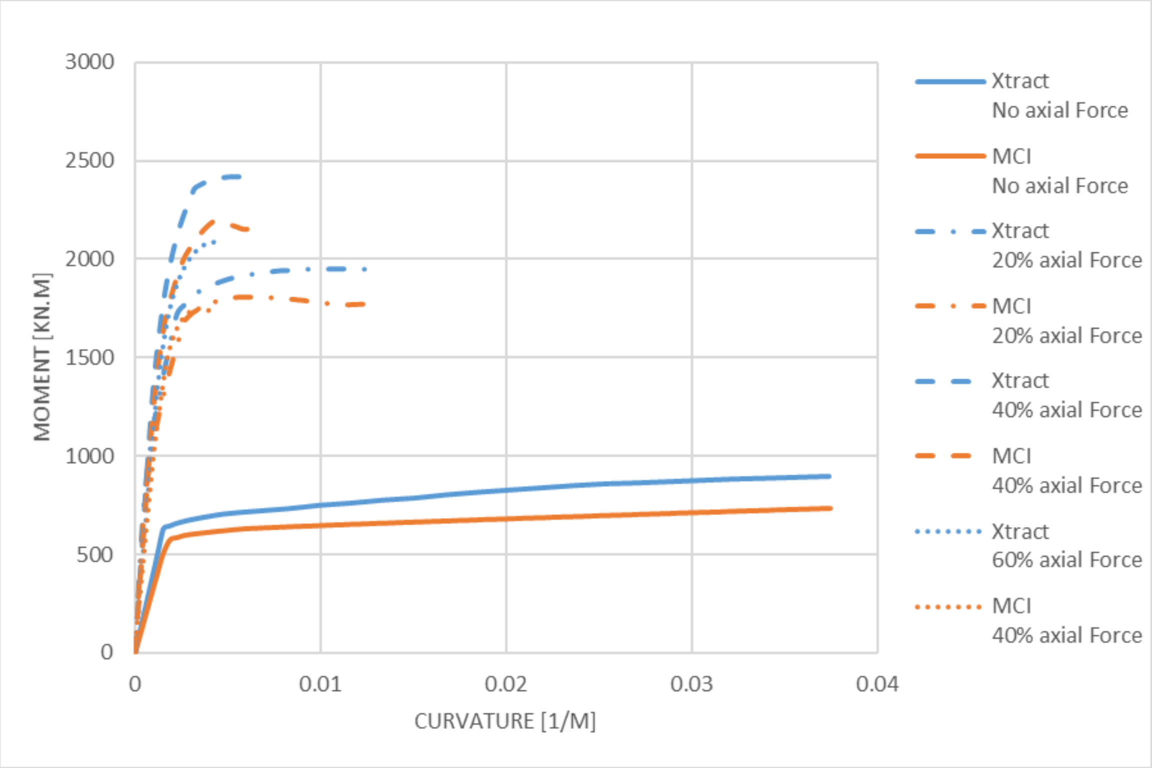


Figure 28:Moment Curvature Curves of Section 3 – Low Strength Materials

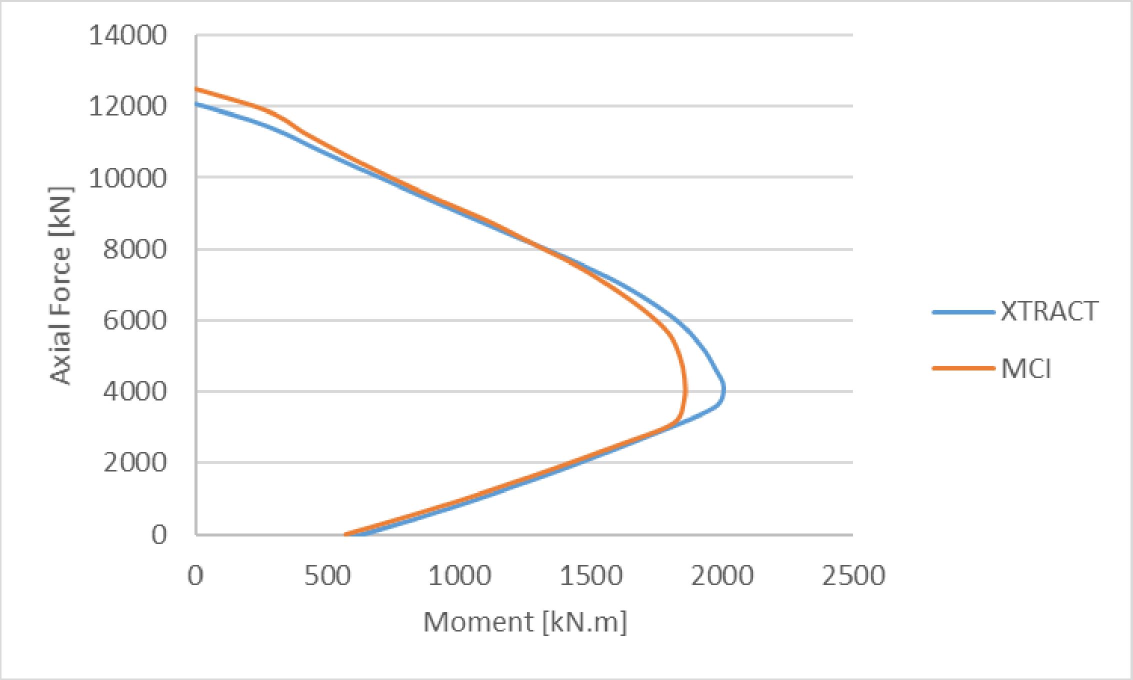


Figure 29:Interaction Curve of Section 3 – Low Strength Materials

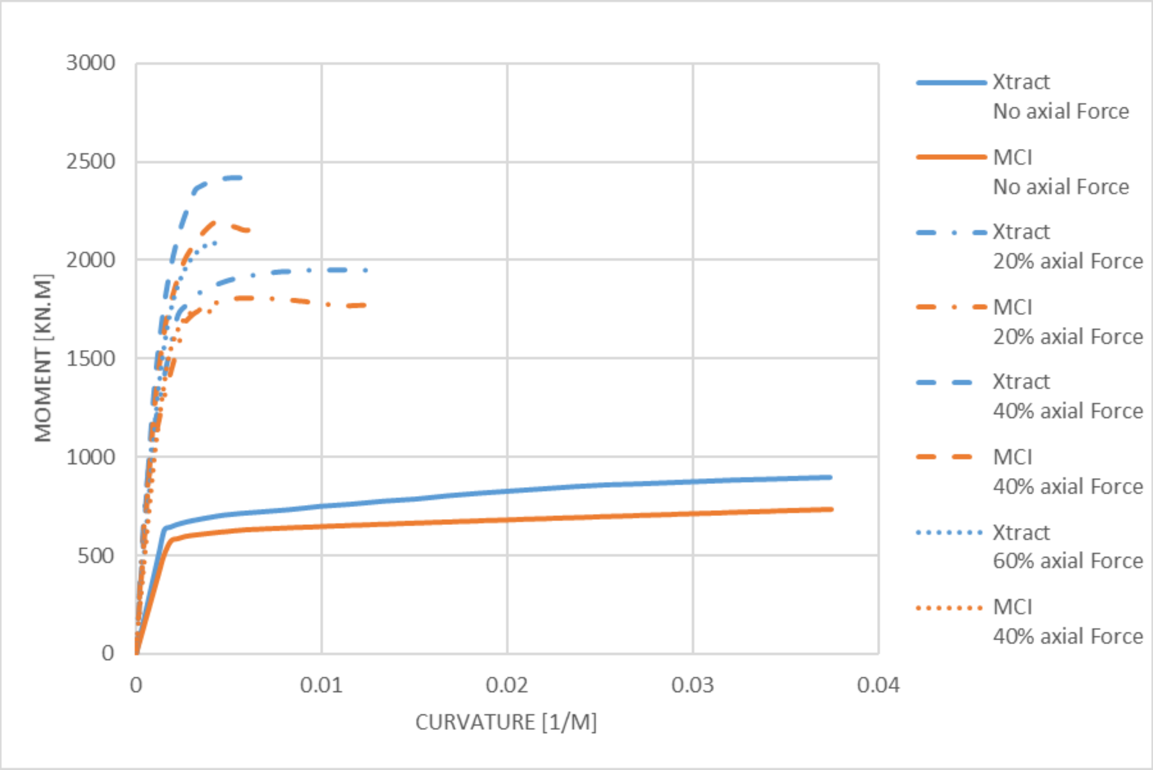


Figure 30:Moment Curvature Curves of Section 3 – Normal Strength Materials

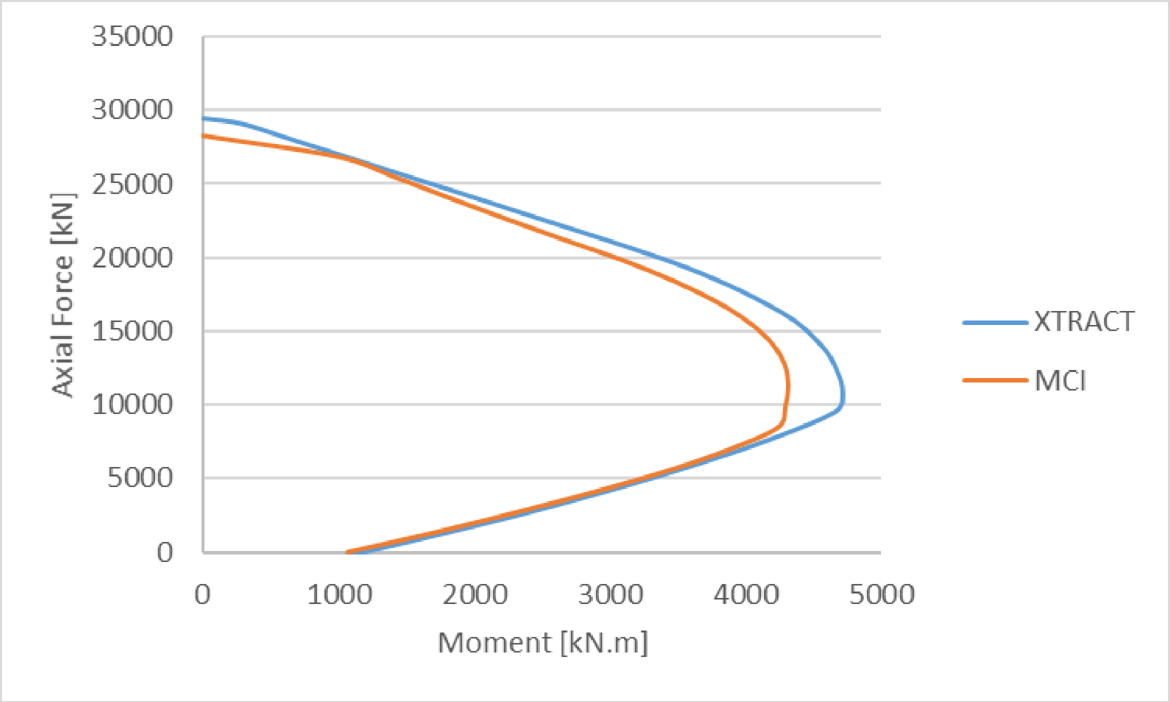


Figure 31:Interaction Curve of Section 3 – Normal Strength Materials

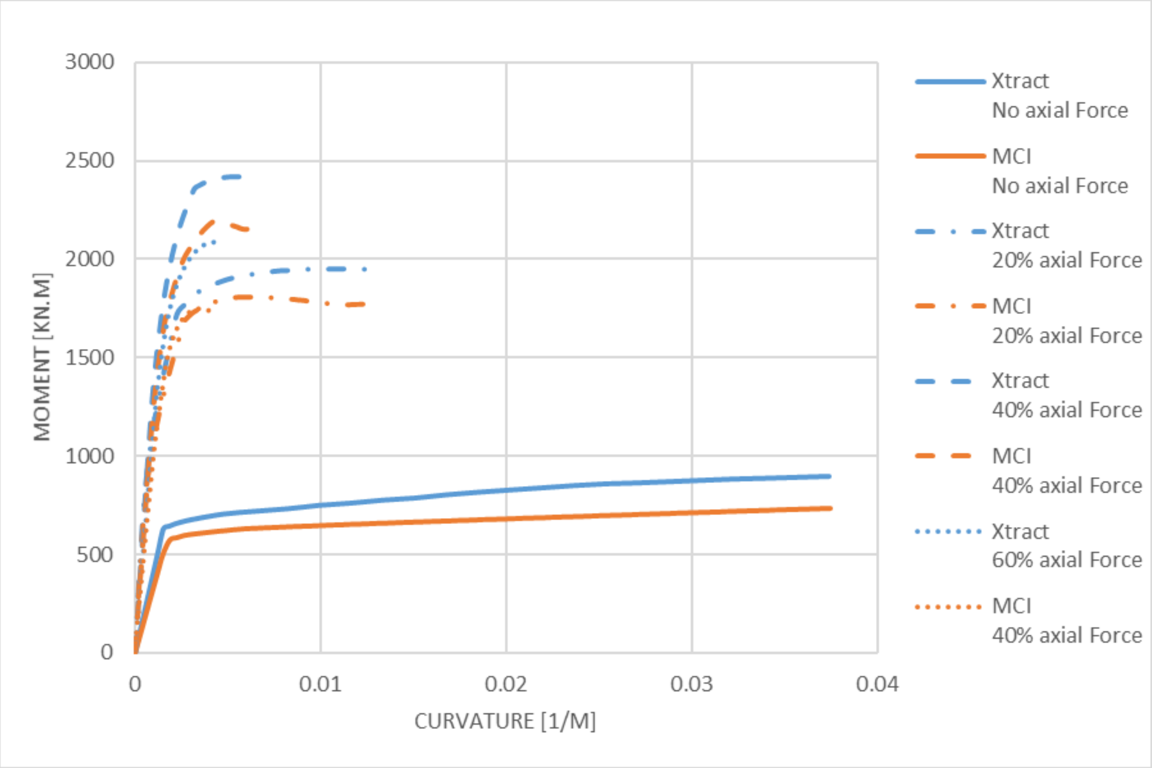


Figure 32:Moment Curvature Curves of Section 3 – High Strength Materials

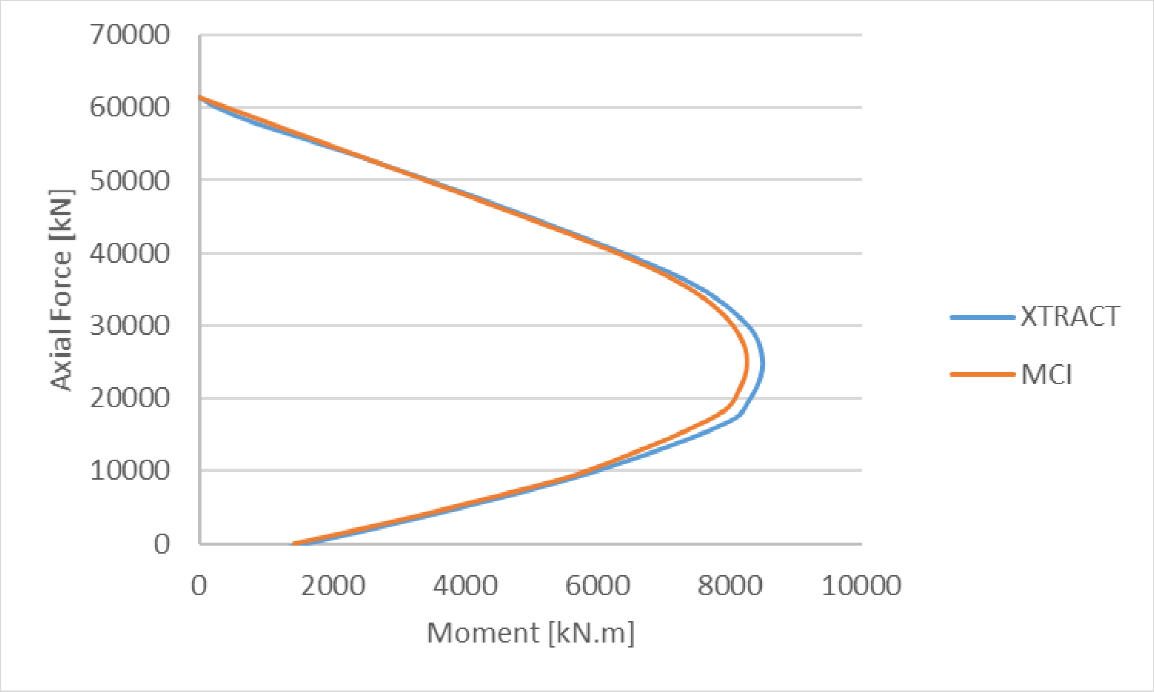


Figure 33:Interaction Curve of Section 3 – High Strength Materials

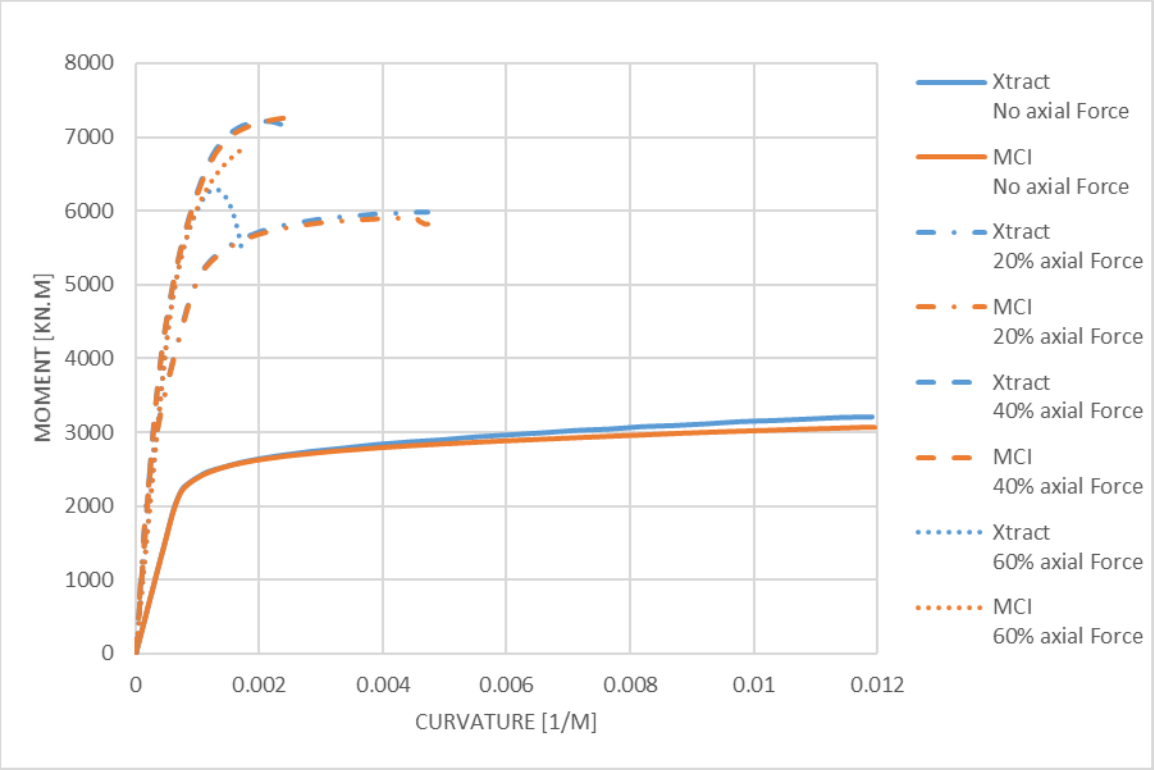


Figure 34:Moment Curvature Curves of Wall Section – Low Strength Materials

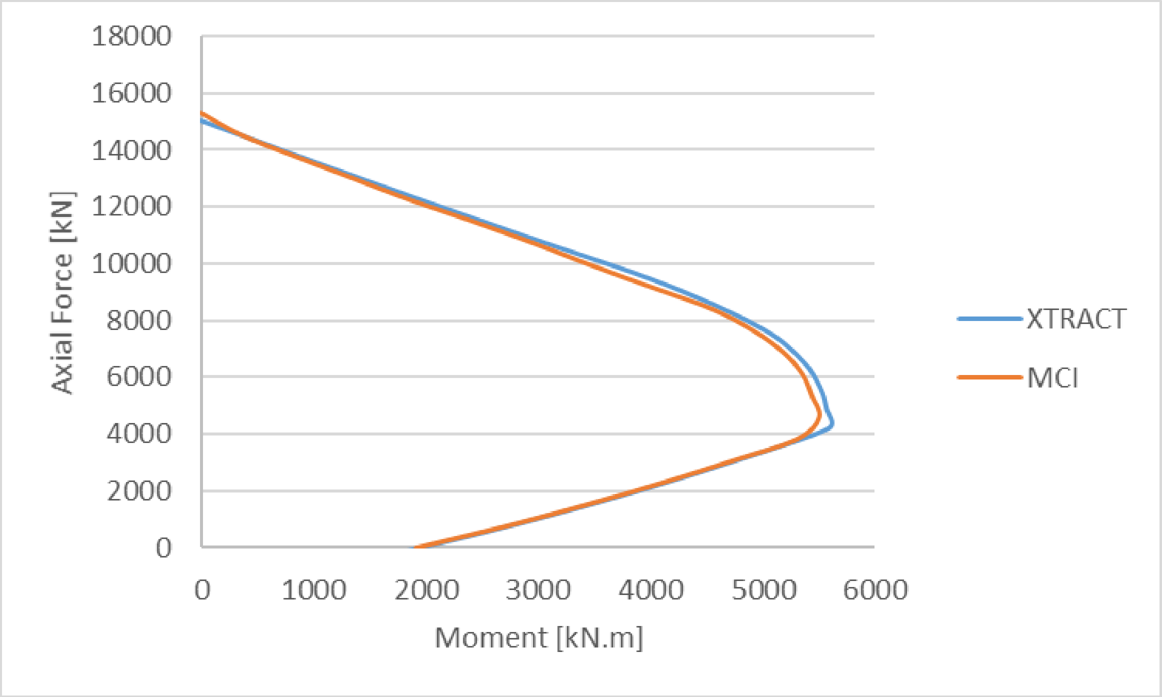


Figure 35:Interaction Curve of Wall Section – Low Strength Materials

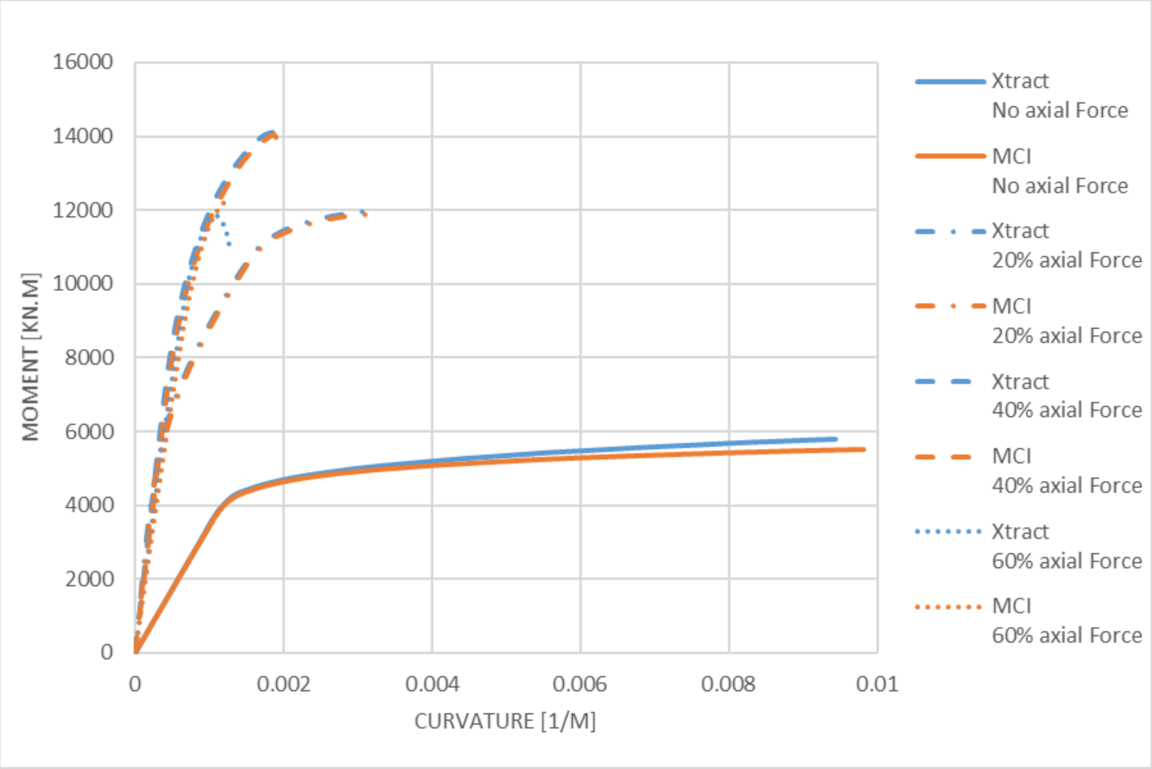


Figure 36:Moment Curvature Curves of Wall Section – Normal Strength Materials

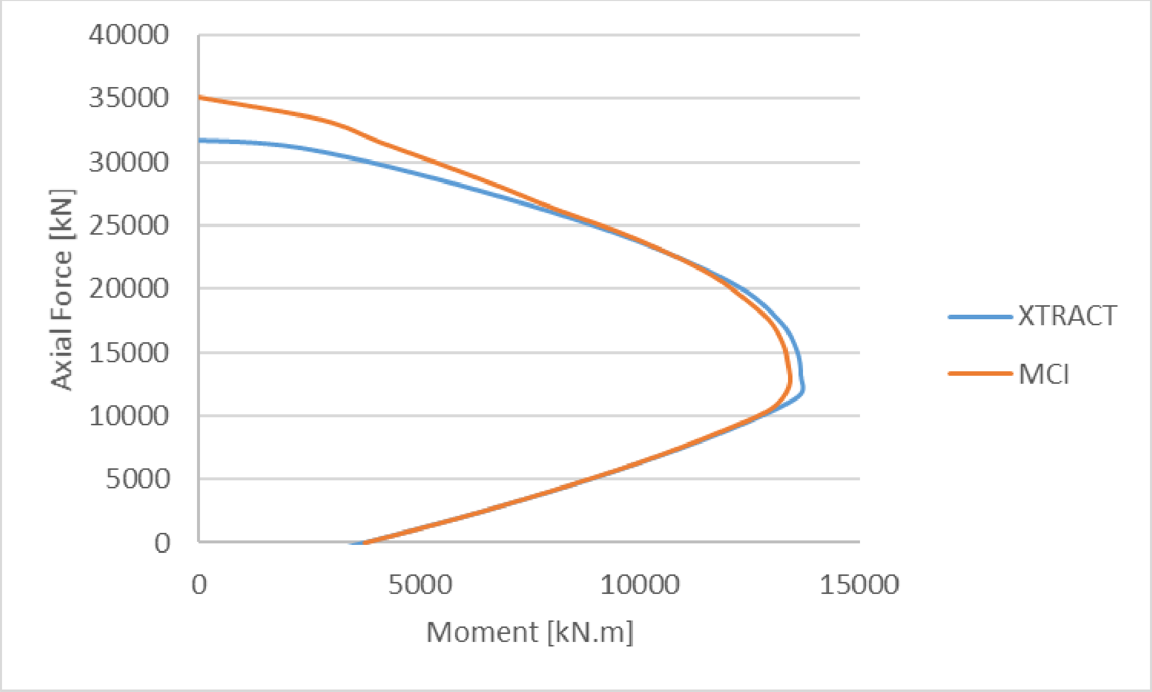


Figure 37:Interaction Curve of Wall Section – Normal Strength Materials

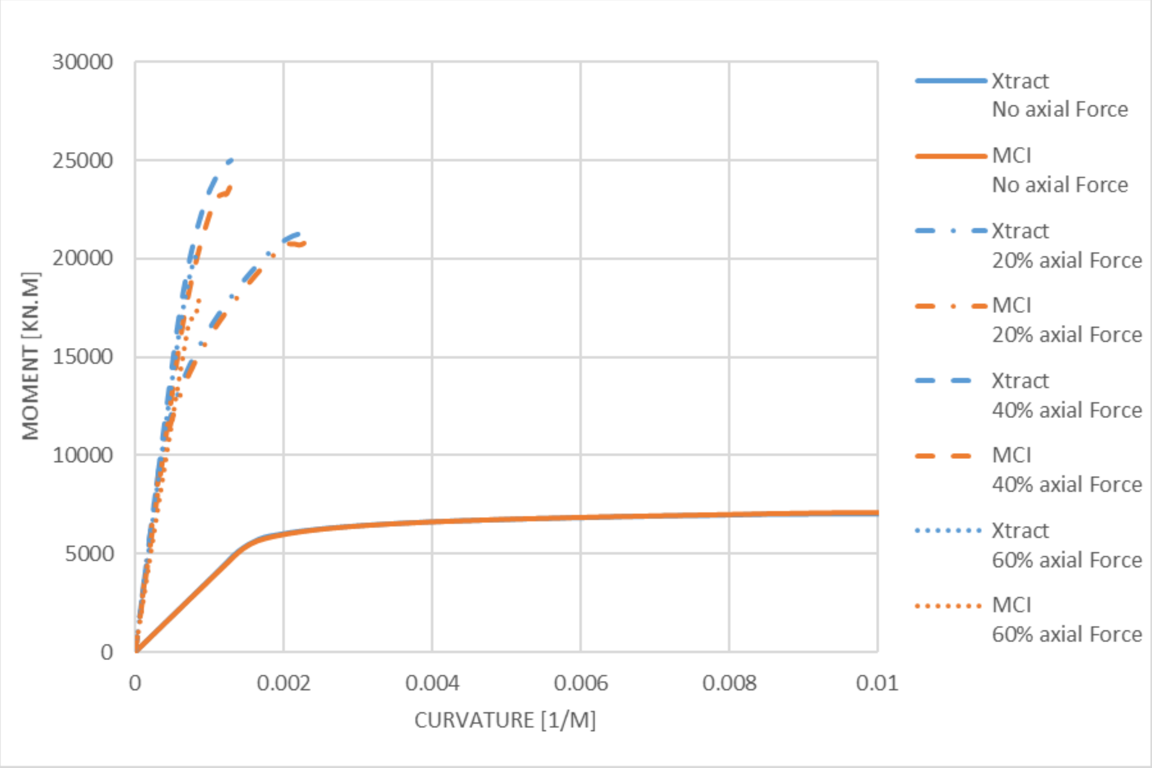


Figure 38:Moment Curvature Curves of Wall Section – High Strength Materials

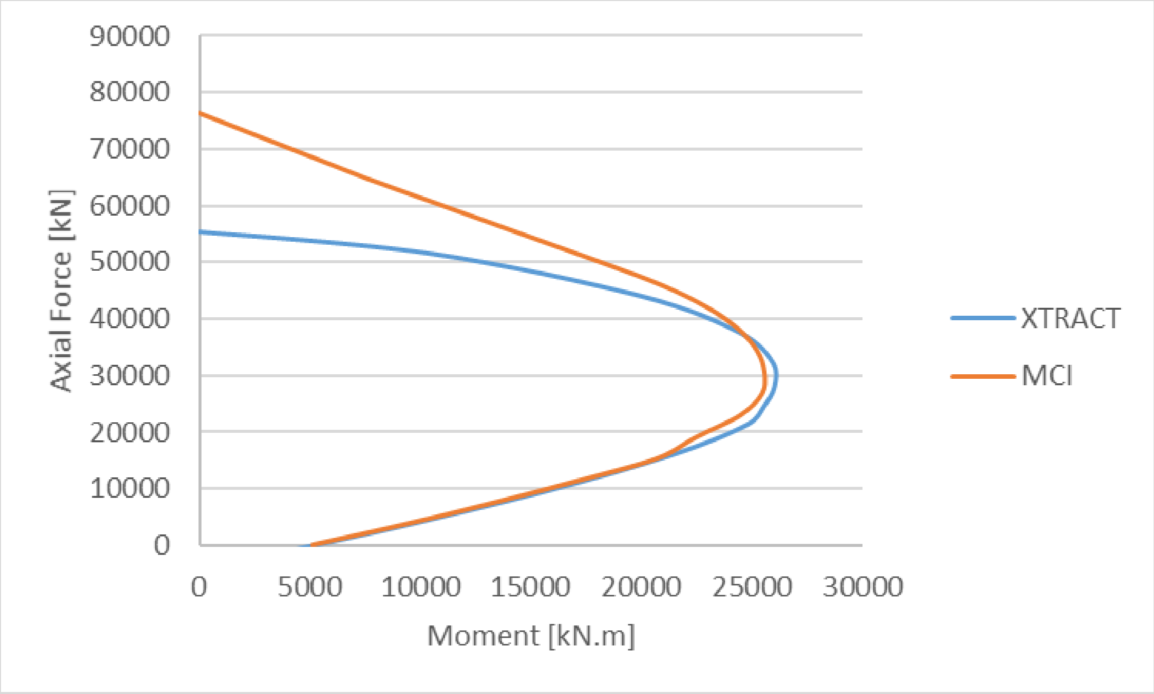
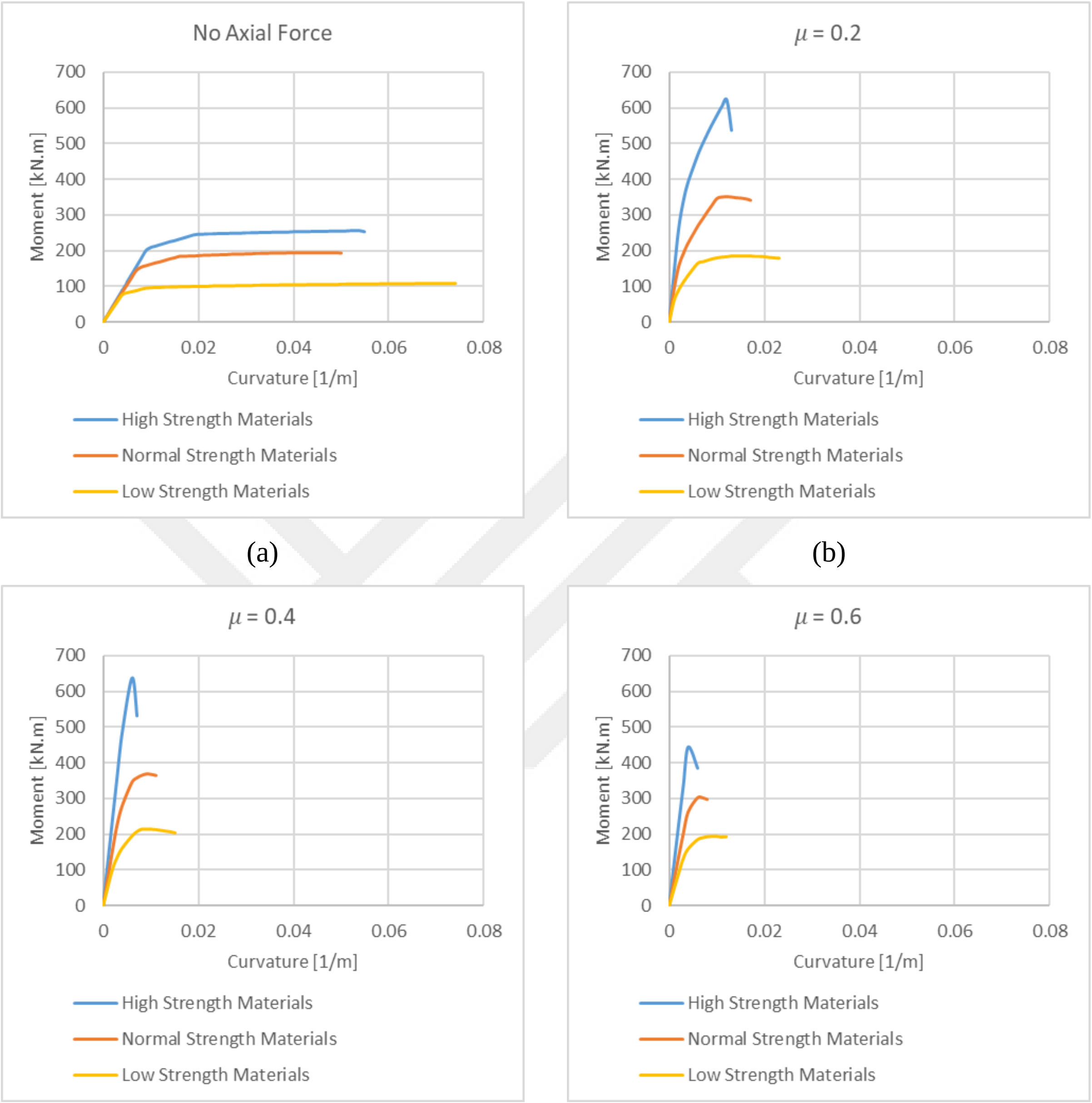


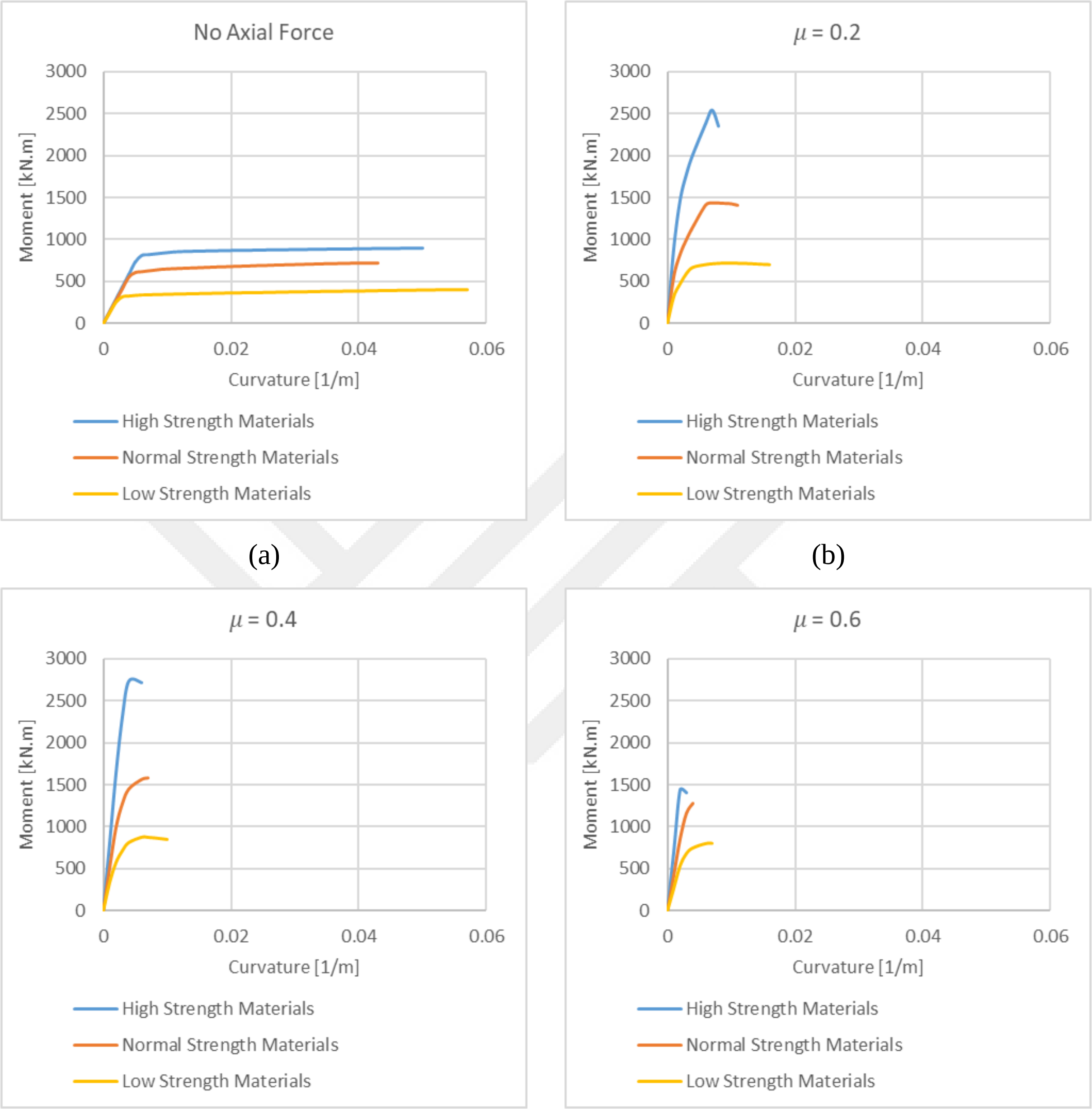
Figure 39:Interaction Curve of Wall Section – High Strength Materials



(a) (b)

(c) (d)

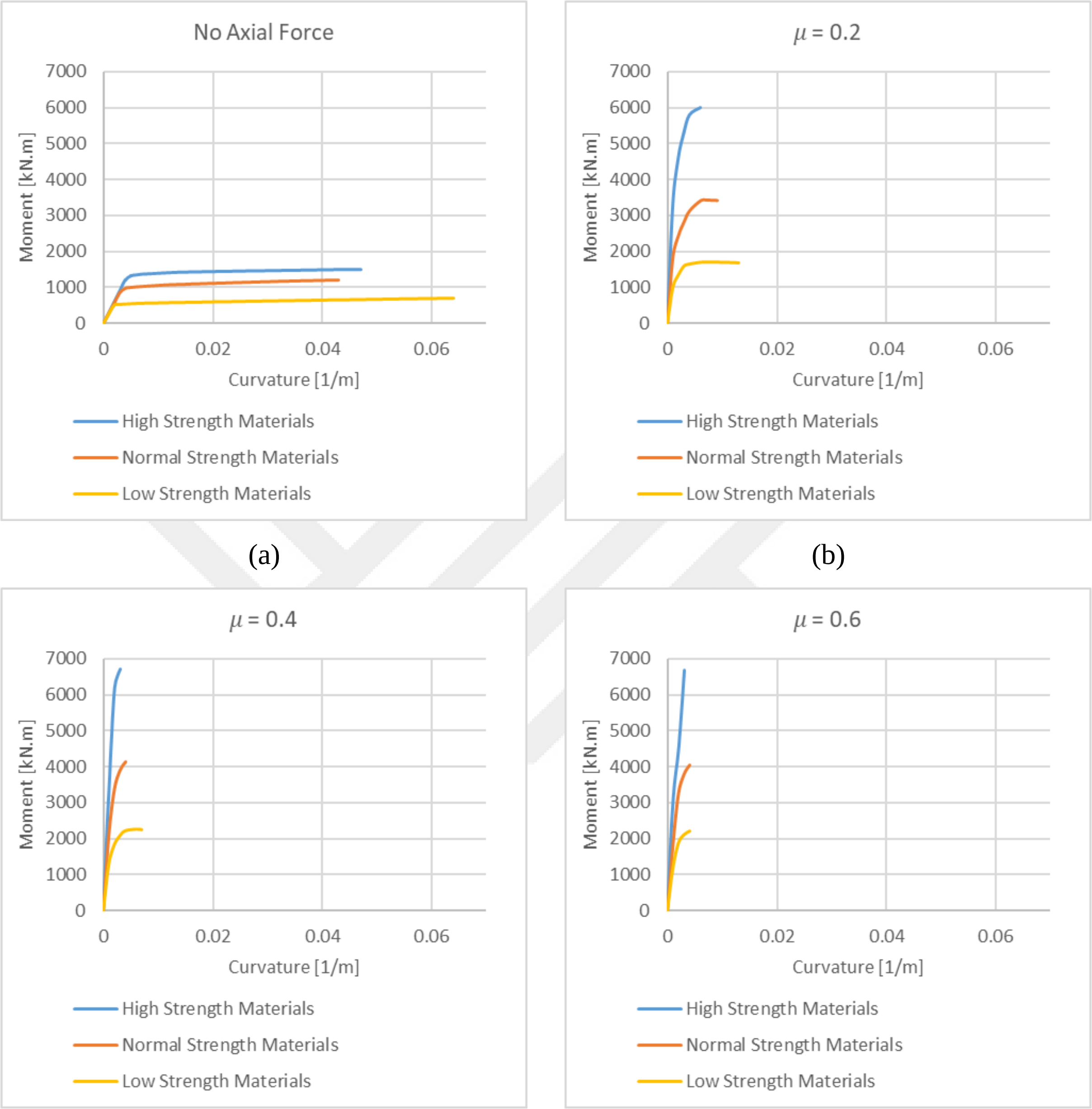
Figure 40: Moment curvature curve of section 1



(a) (b)

(c) (d)

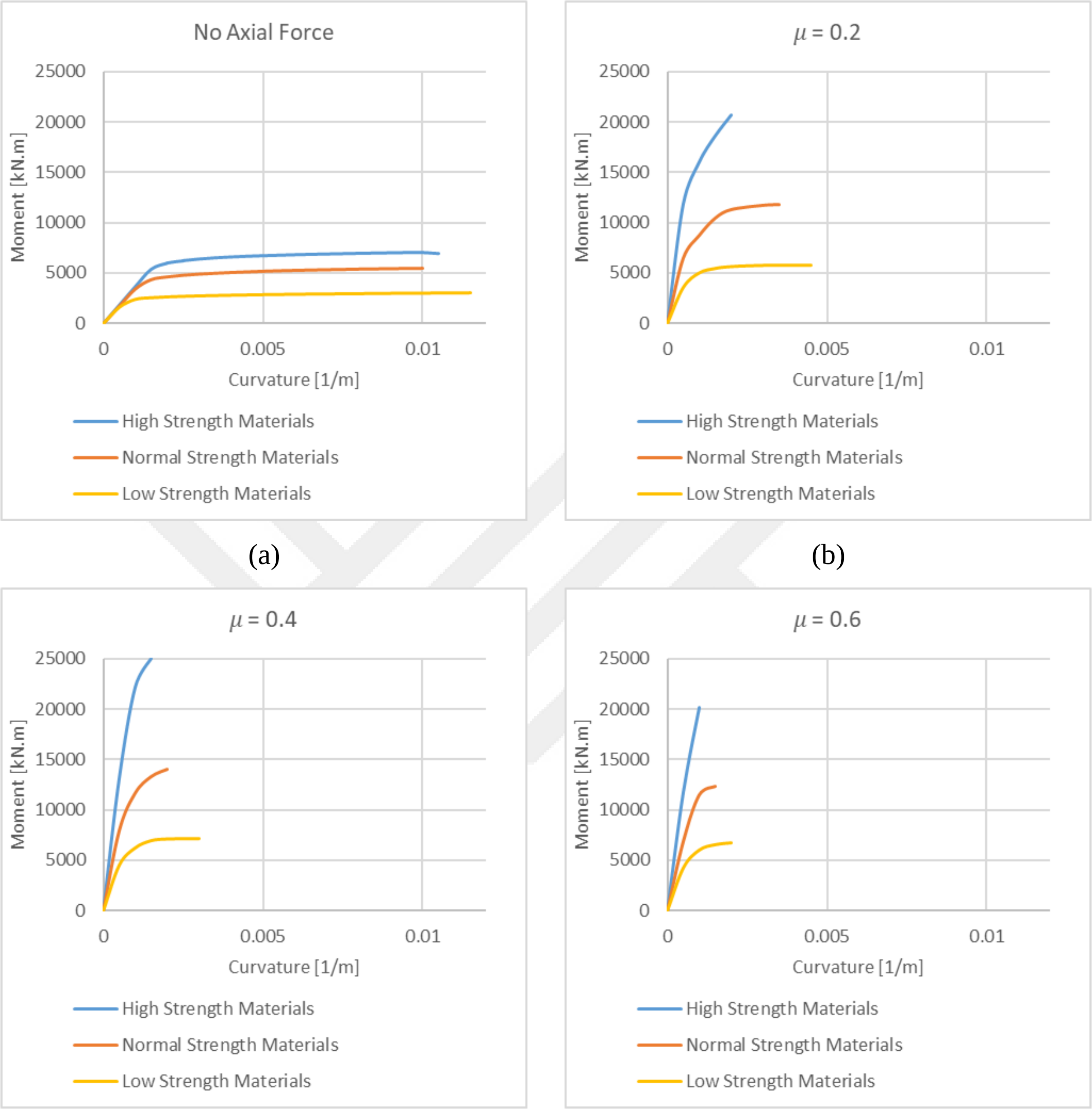
Figure 41: Moment curvature curve of section 2



(a) (b)

(c) (d)

Figure 42: Moment curvature curve of section 3


No Axial Force

$\mu = 0.2$

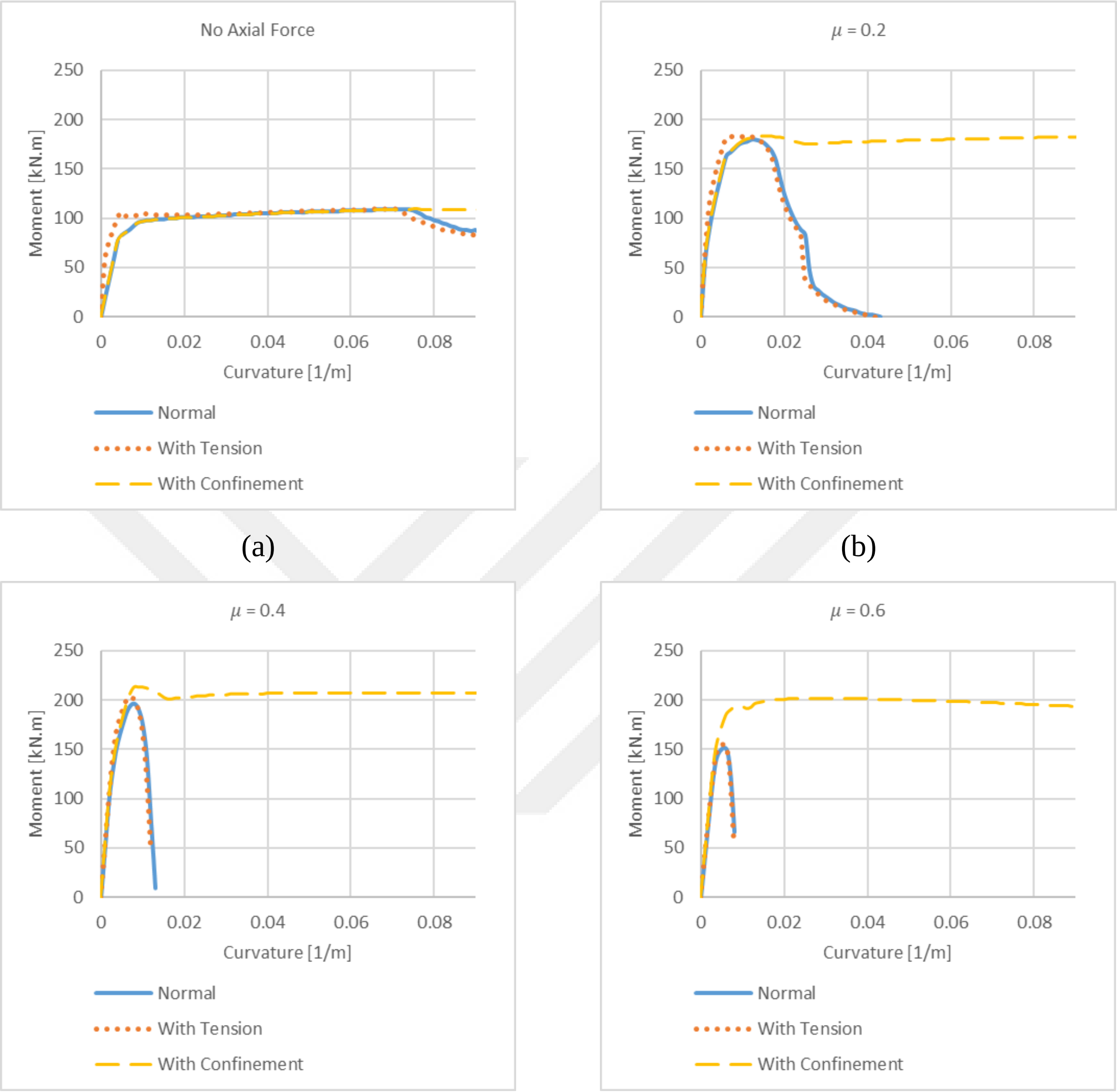
$\mu = 0.4$

$\mu = 0.6$

(a) (b)

(c) (d)

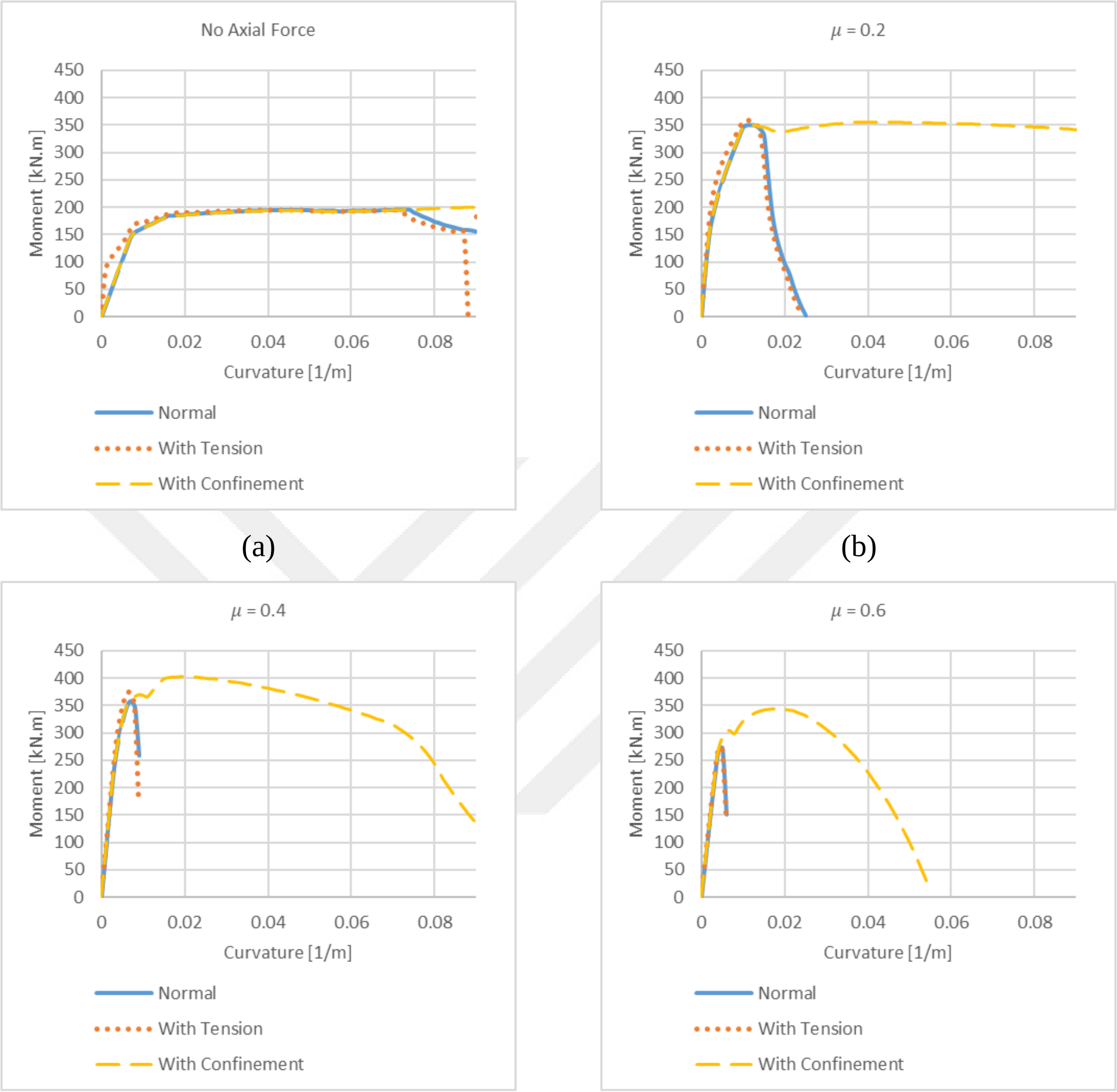
Figure 43: Moment curvature curve of wall section



(a) (b)

(c) (d)

Low Strength Materials



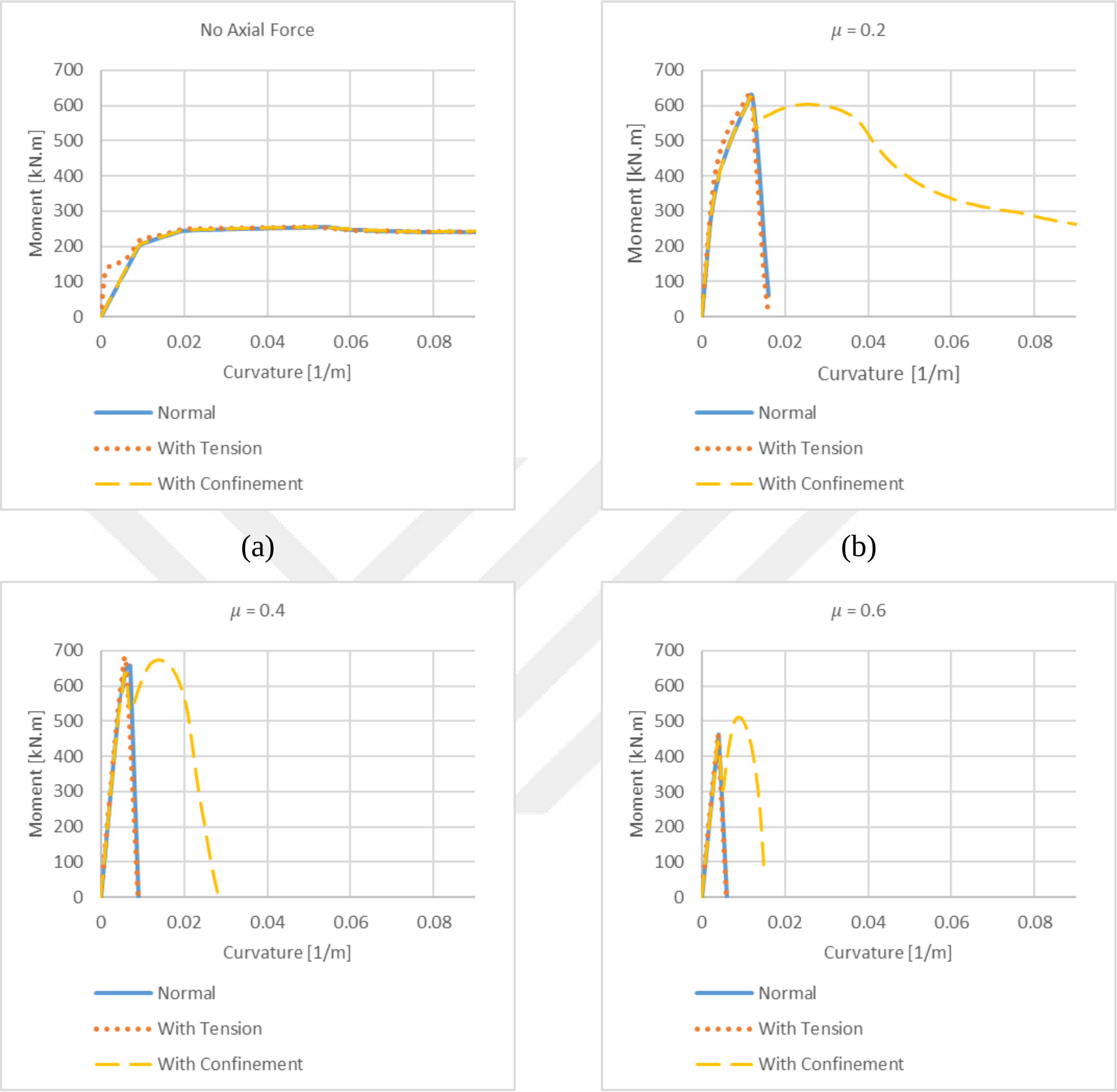
(a)

(b)

(c)

(d)

Normal Strength Materials

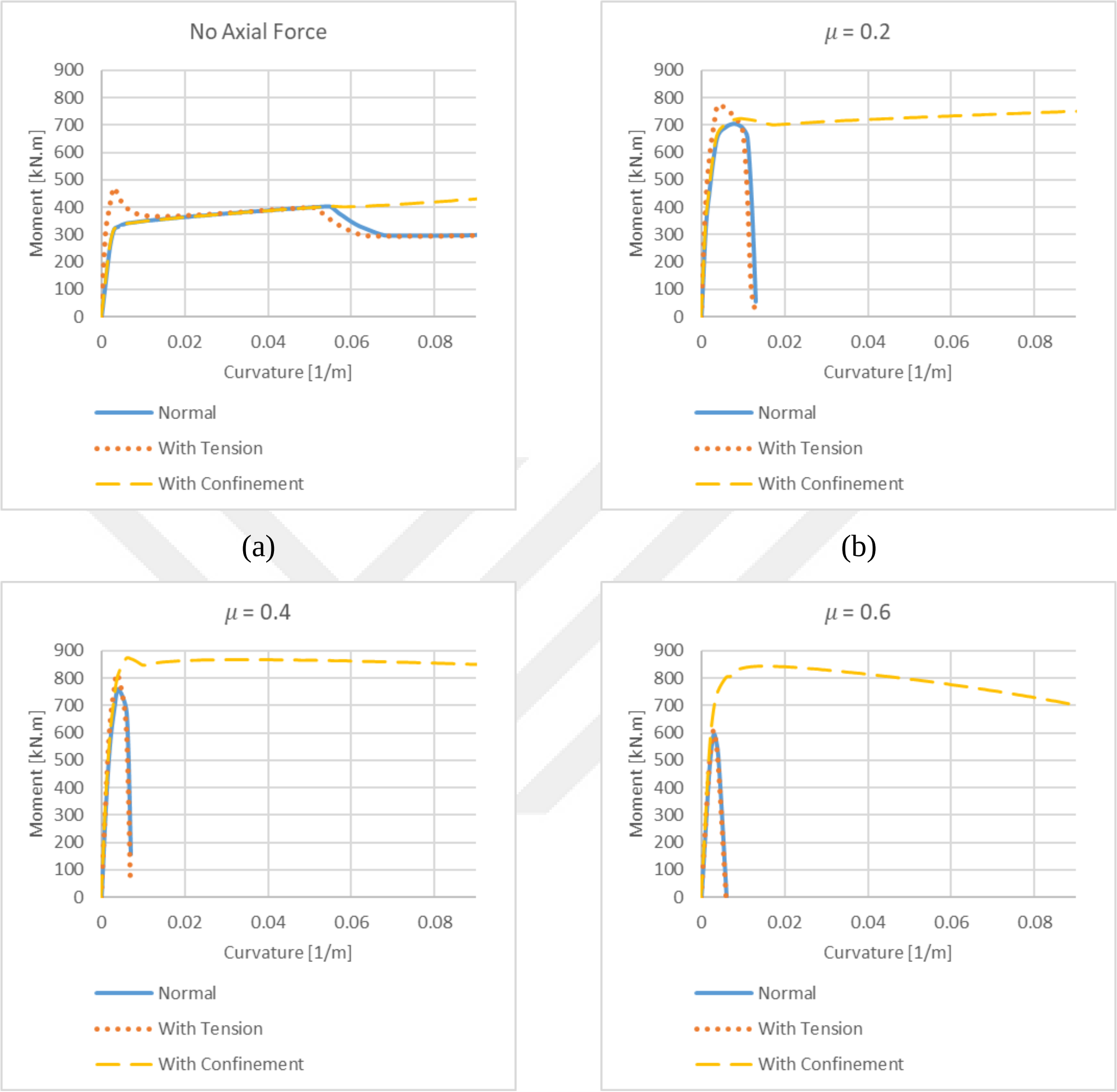


(a) (b)

(c) (d)

High Strength Materials

Figure 44: Moment curvature curve of section 1



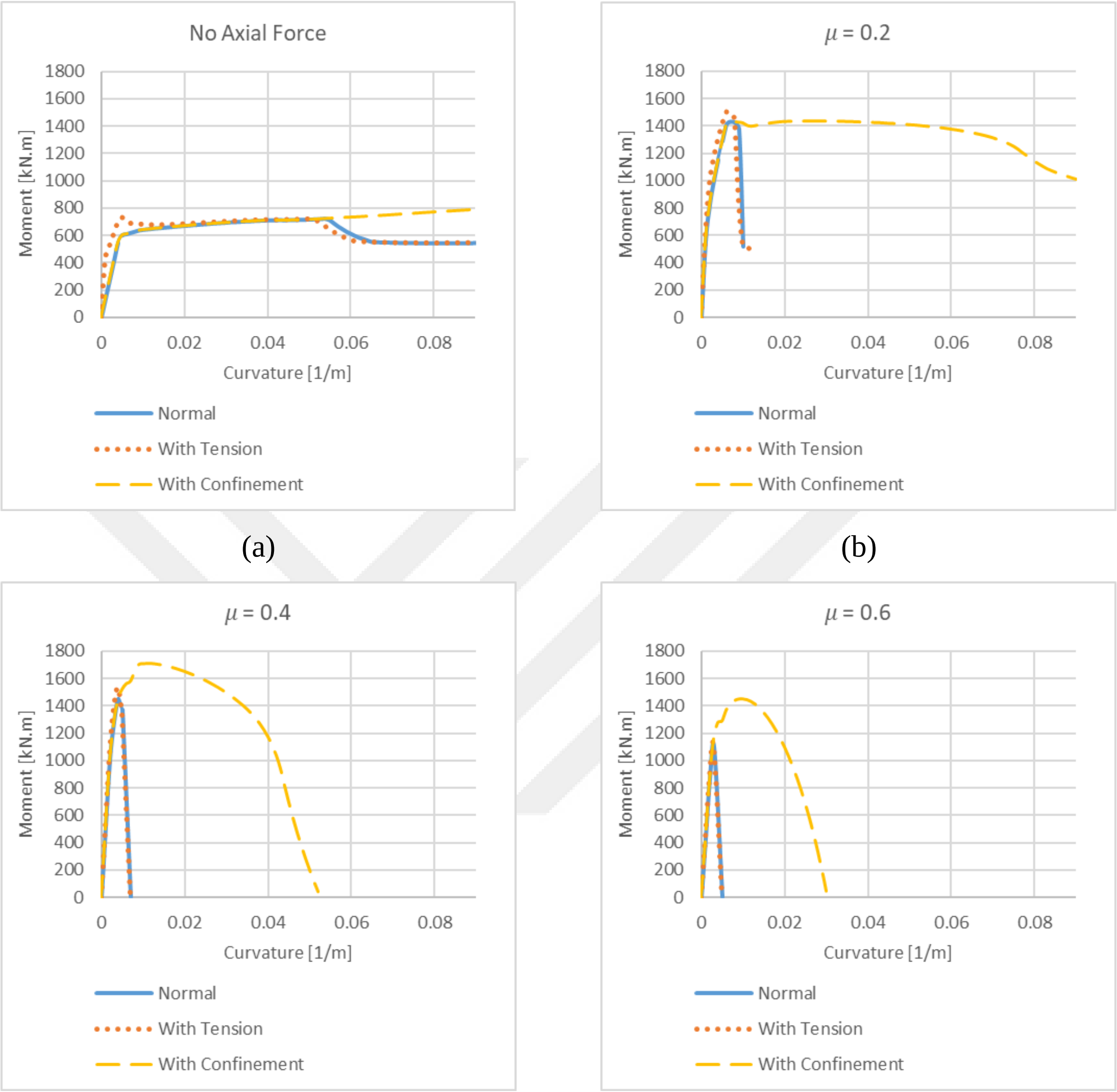
(a)

(b)

(c)

(d)

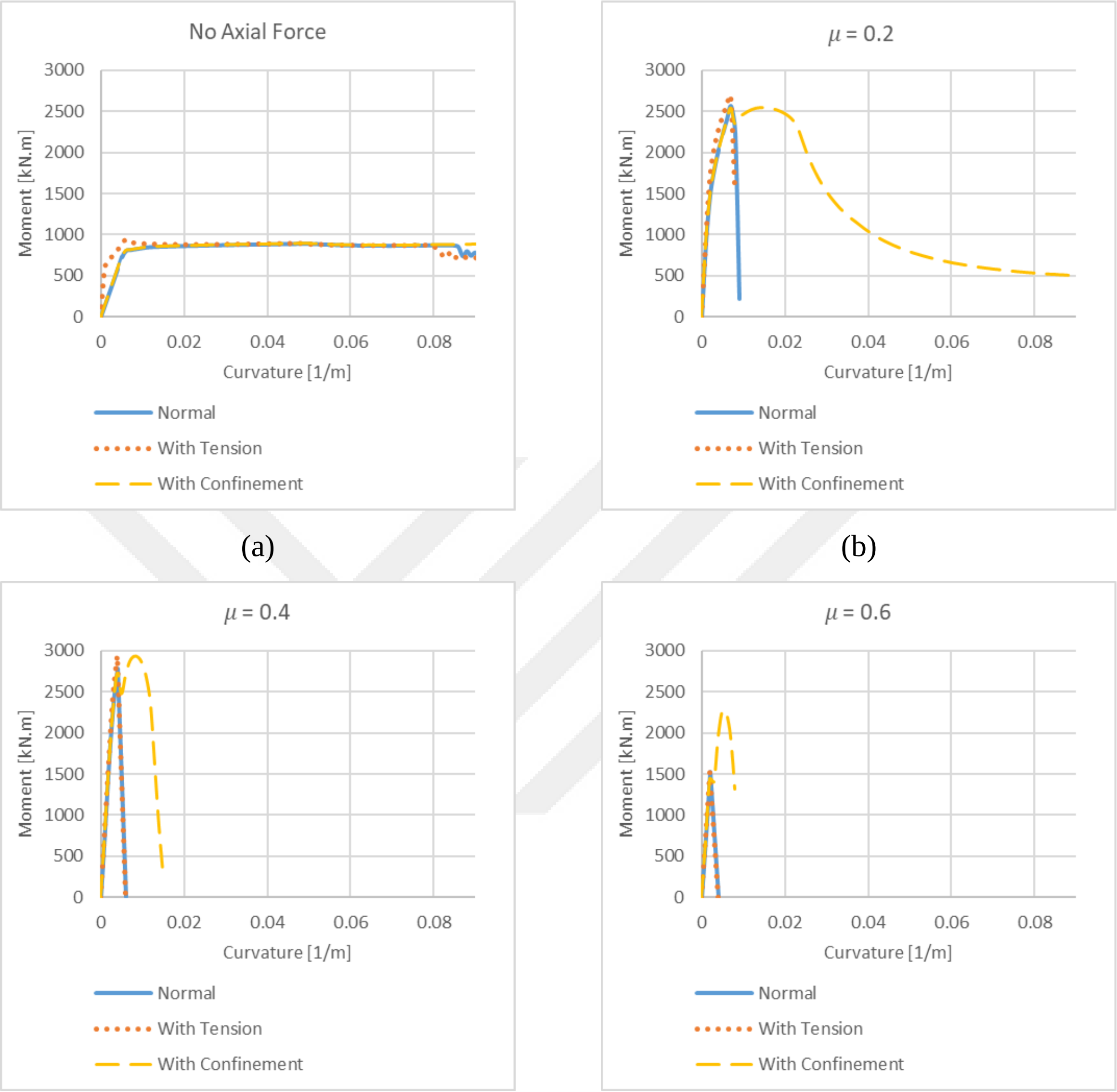
Low Strength Materials



(a) (b)

(c) (d)

Normal Strength Materials

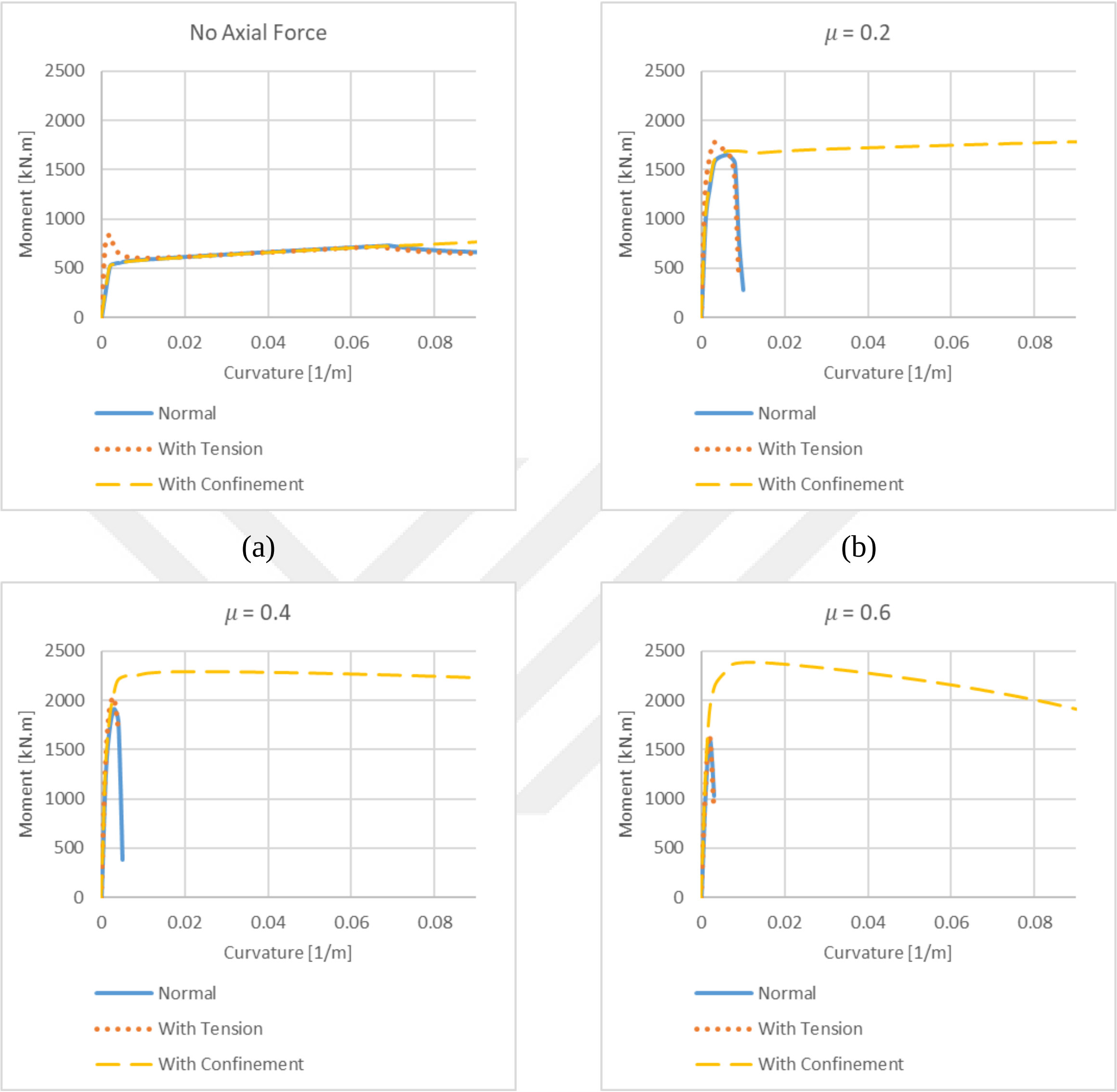


(a) (b)

(c) (d)

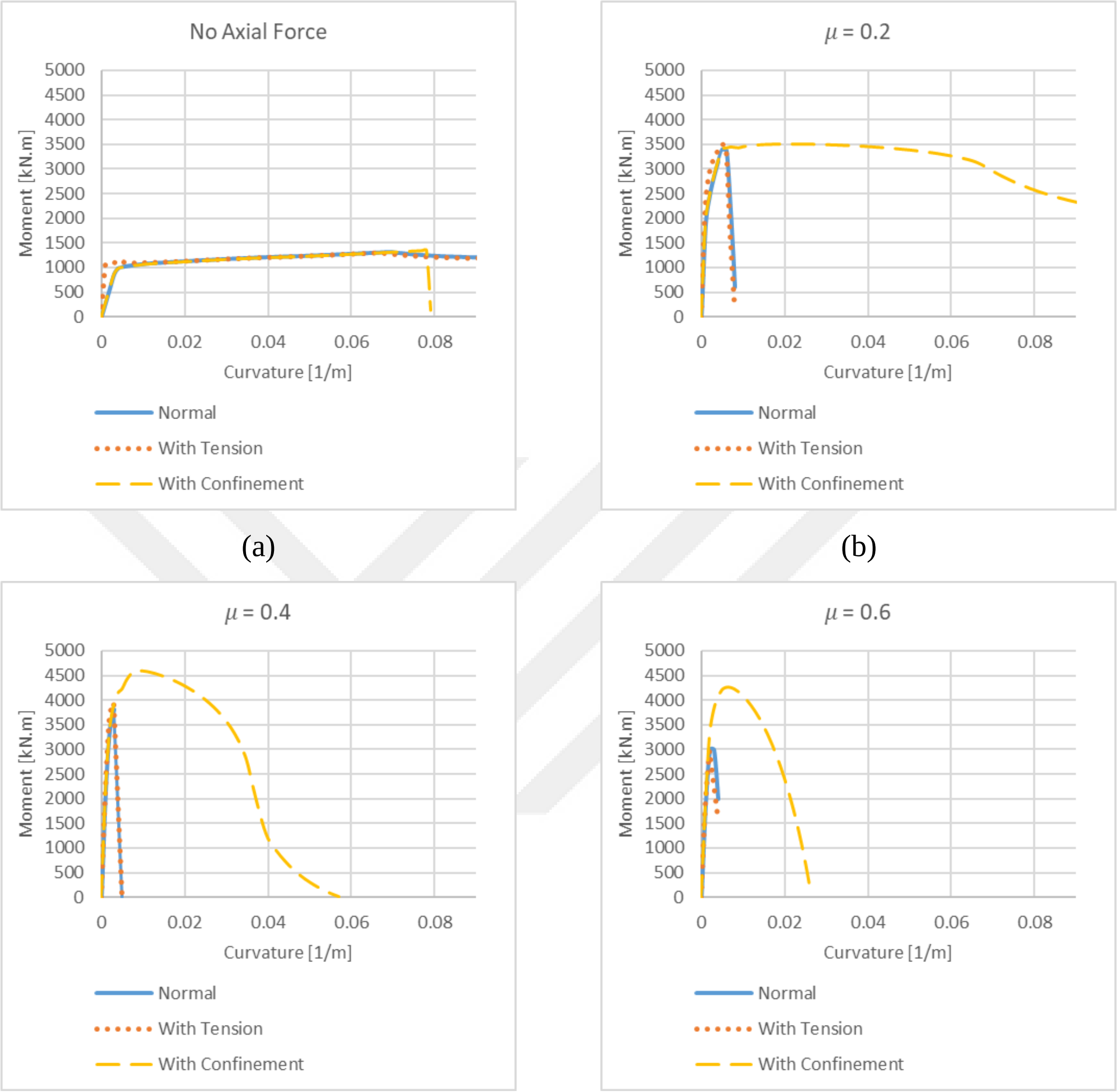
High Strength Materials

Figure 45: Moment curvature curve of section 2



(a) (b) (c) (d)

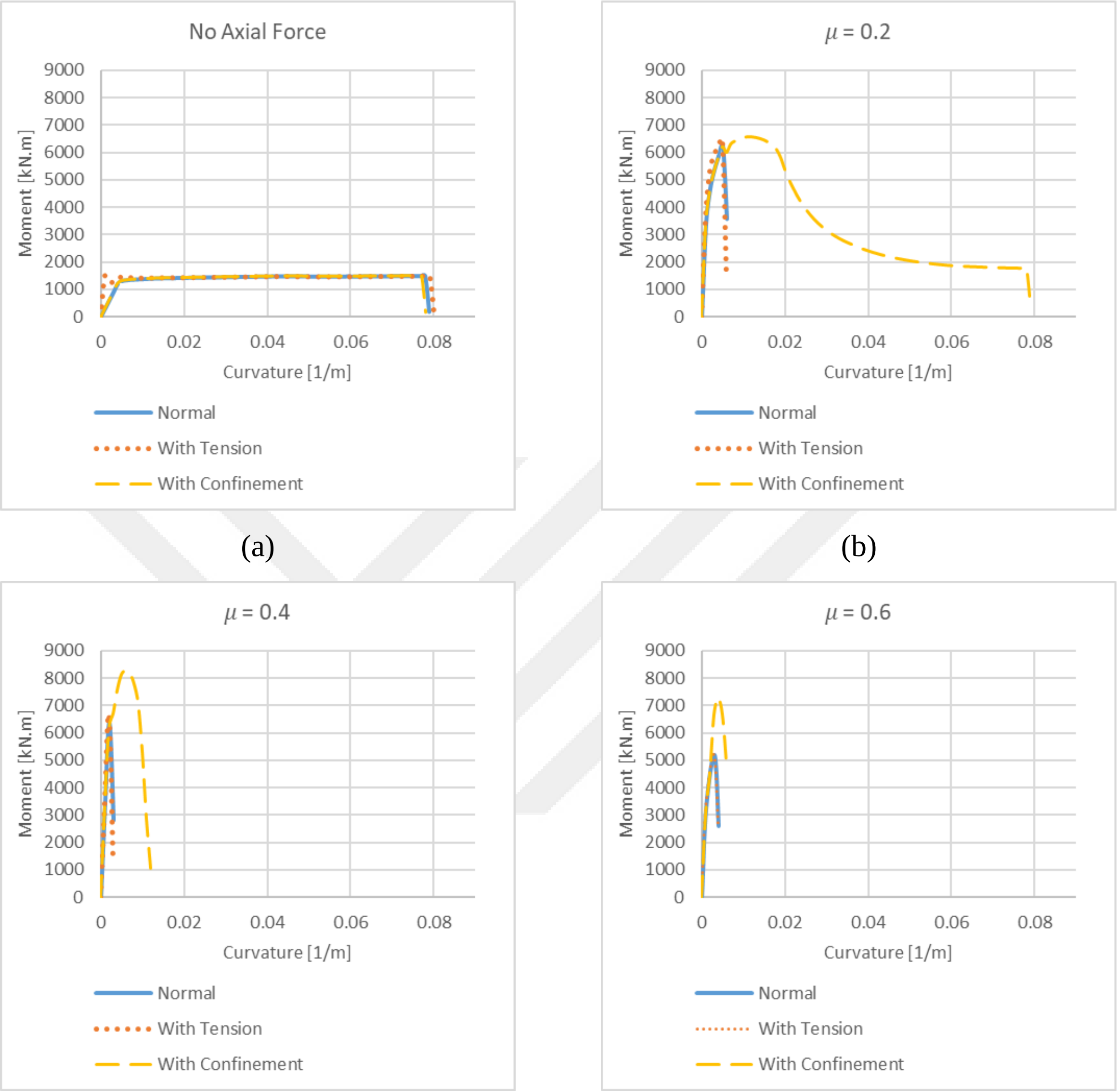
Low Strength Materials



(a) (b)

(c) (d)

Normal Strength Materials

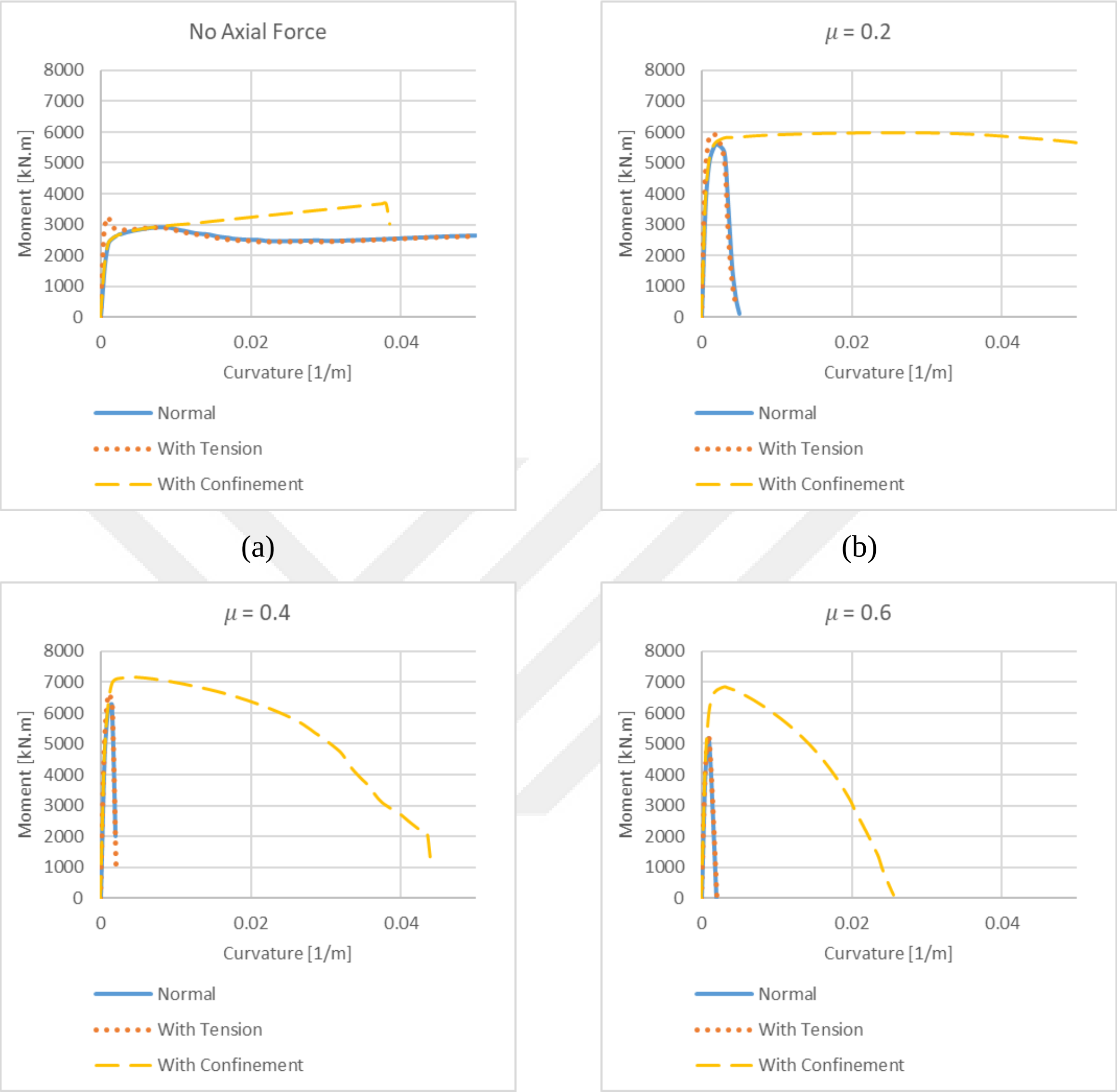


(a) (b)

(c) (d)

High Strength Materials

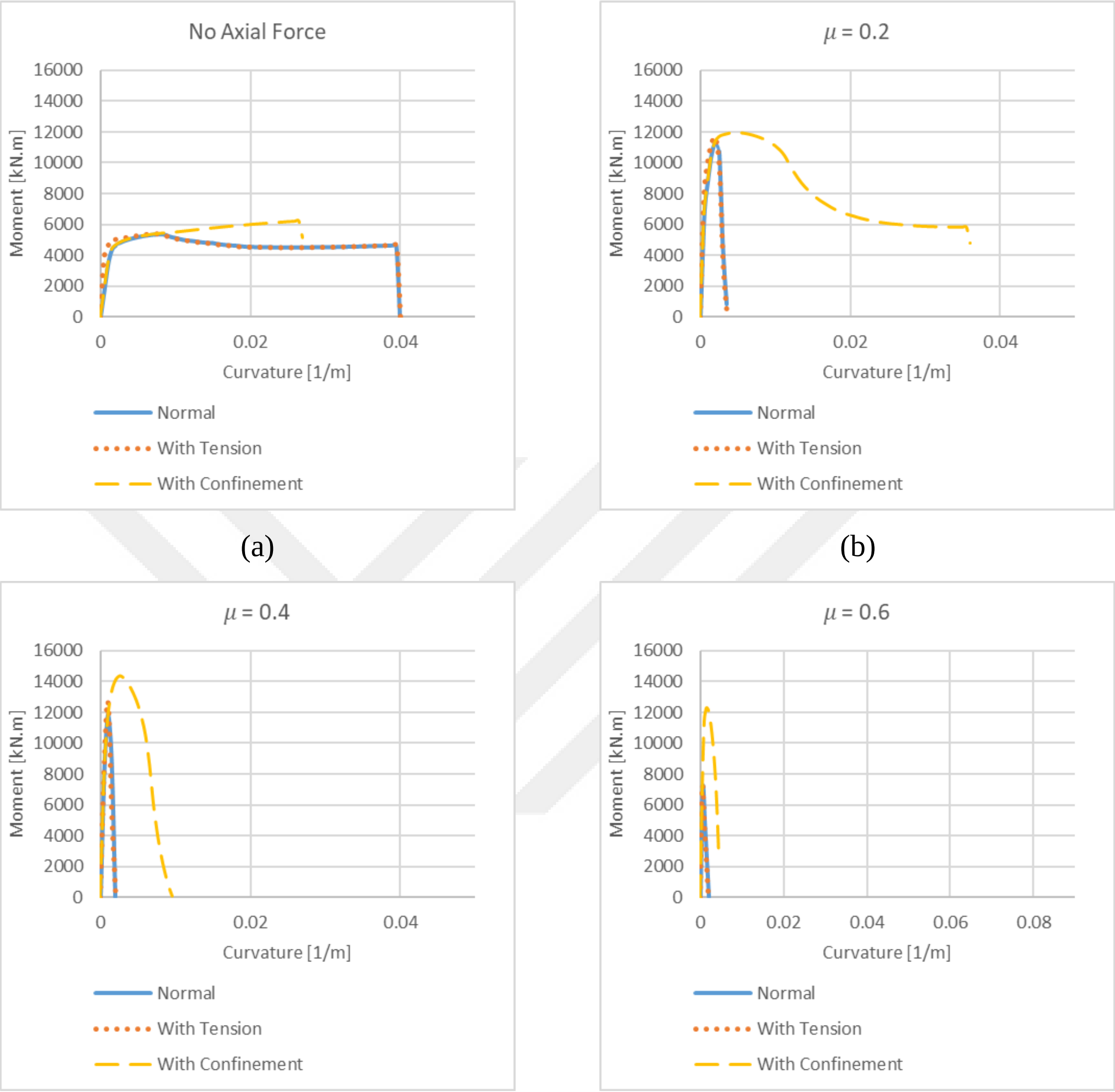
Figure 46: Moment curvature curve of section 3



(a) (b)

(c) (d)

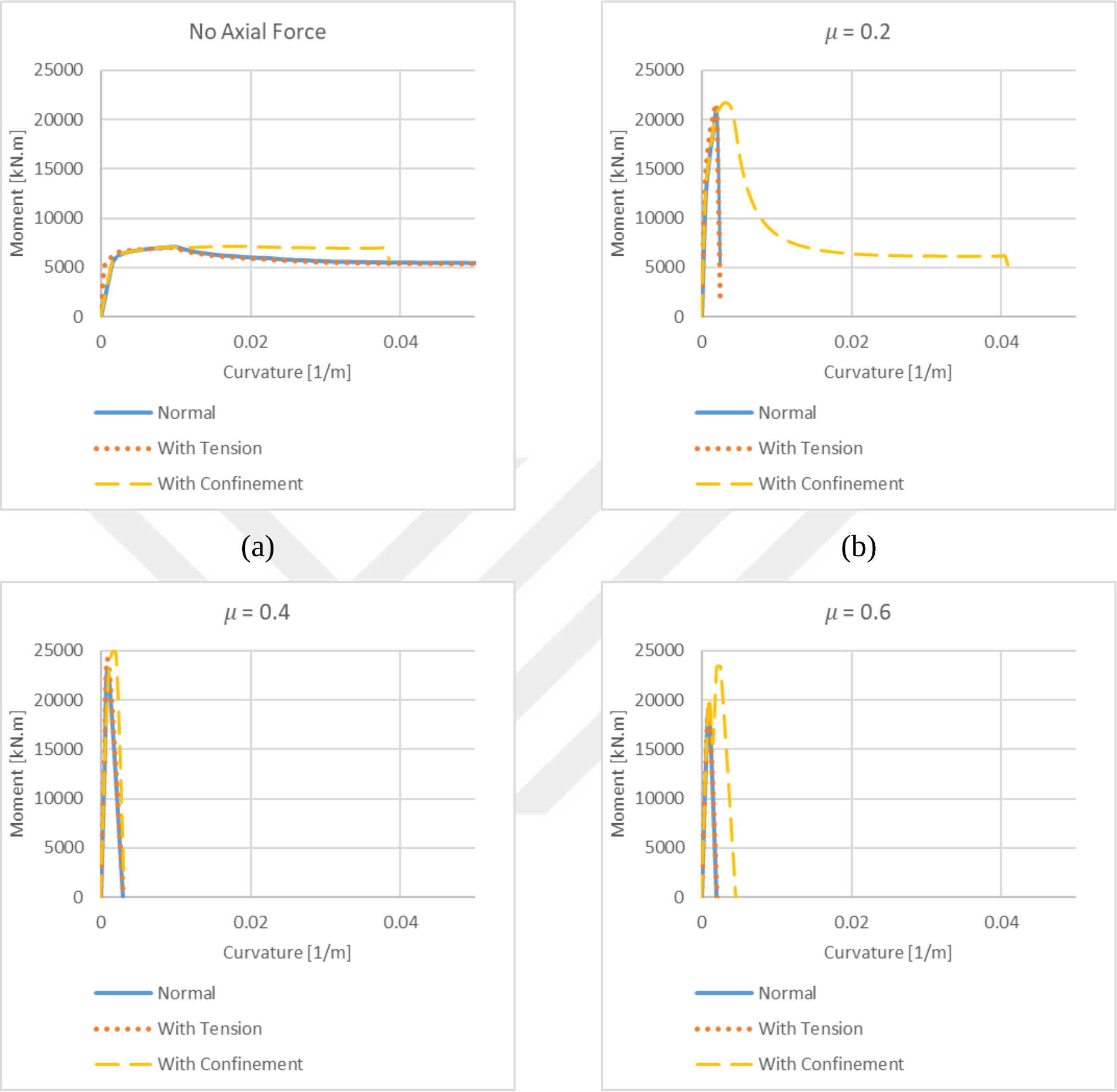
Low Strength Materials



(a) (b)

(c) (d)

Normal Strength Materials



(a) (b)

(c) (d)

High Strength Materials

Figure 47: Moment curvature curve of the wall section

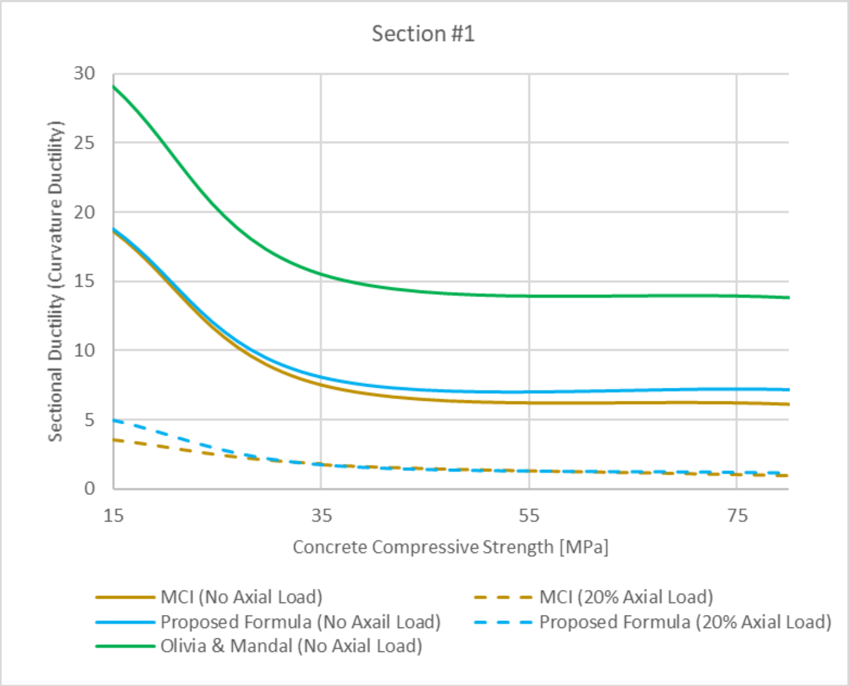


Figure 48: The Influence of Material Properties on Curvature Ductility of Section #1

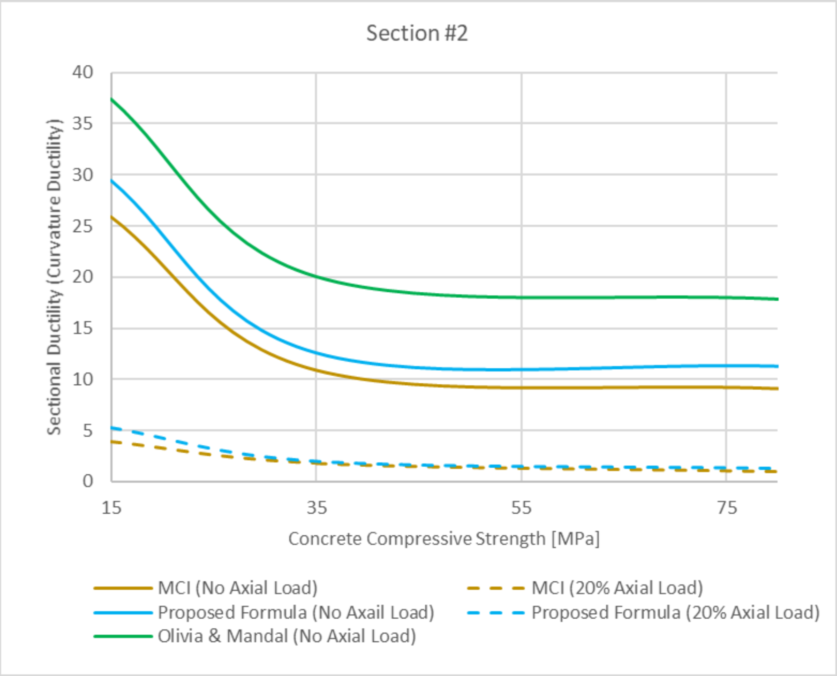


Figure 49: The Influence of Material Properties on Curvature Ductility of Section #2

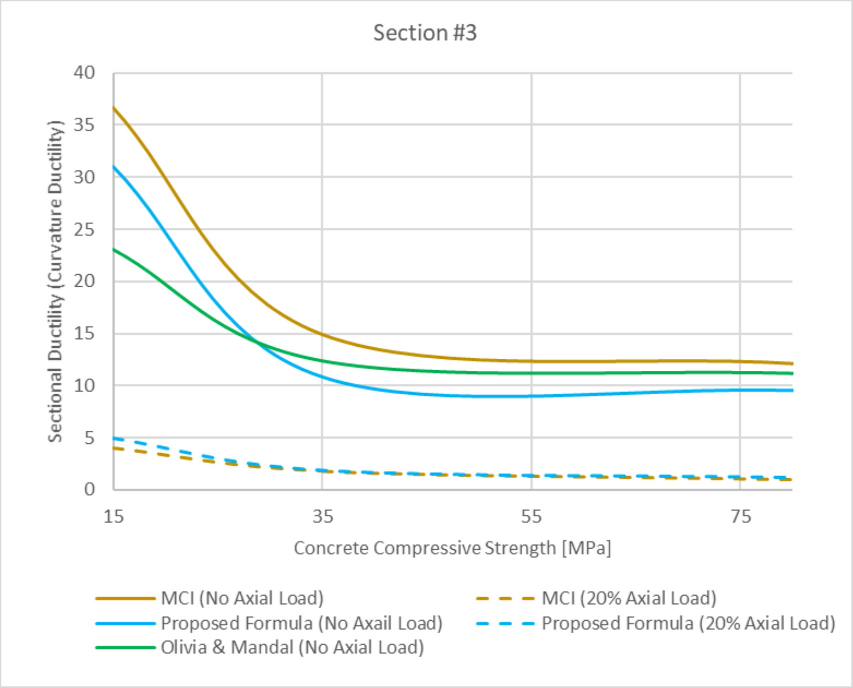


Figure 50: The Influence of Material Properties on Curvature Ductility of Section #3

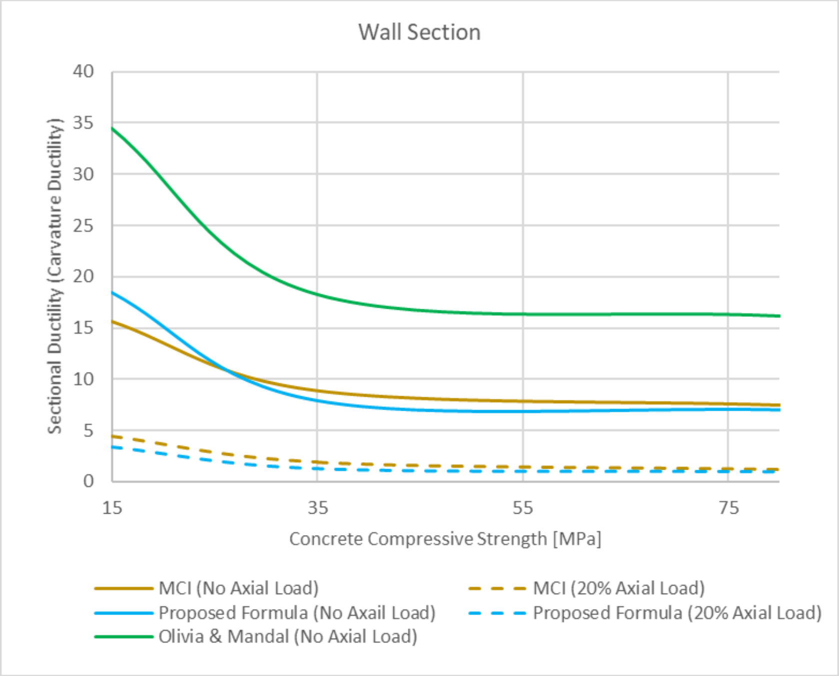


Figure 51: The Influence of Material Properties on Curvature Ductility of Wall Section

APPENDIX II: CODE WRITTEN FOR MCI SOFTWARE

```
Imports System.Windows.Forms.DataVisualization.Charting
Public Class MainForm
    Public section_height, section_width, concrete_cover, unconfined_layer_thickness As Double
    Public depth_of_first_row_top_rein, depth_of_top_rein, depth_of_first_row_middle_rein, depth_of_first_row_bottom_rein, depth_of_bottom_rein As Double
    Public top_rein_dim, middle_rein_dim, bottom_rein_dim, stirrups_dim As Double
    Public top_rein_num_per_row, middle_rein_num_per_row, bottom_rein_num_per_row As Integer
    Public top_rein_rows_spacing, middle_rein_rows_spacing, bottom_rein_rows_spacing, stirrups_spacing As Double
    Public top_rein_rows_num, middle_rein_rows_num, bottom_rein_rows_num, layers_num As Integer
    Public layer_thickness, layer_thickness_new As Double
    Public section_area, top_rein_row_area, middle_rein_row_area, bottom_rein_row_area, rein_area As Double
    Public E_s, E_c, f_cm, f_ccm, f_cu, f_ccu, f_y, ep_y, ep_u, f_u, f_yt, f_ctm, f_ctu, ep_cm, ep_ccm, E_des, ep_cu, ep_ccu, ep_ccu0, ep_cu0, ep_ctm, ep_ctu, ep_ctu0, C_s, curvature, X_m, X_mm, mio As Double
    Public curvatures_iterations As Integer
    Public steel_moment, steel_force, conc_moment, conc_force, applied_force, beta As Double
    Public max_moment_piont, max_curvature_point, max_moment_force_piont, interaction_points As Integer
    Public max_momnet_value, max_curvature_value, max_moment_force_value As Double
    Public confined, limit_check(8), failure_at_cu, failure_at_fu, failure_at_fy, interaction As Boolean
    Public limit_iteration(8) As Integer
    Public concrete_reduction_factor, steel_reduction_factor, force_reduction_factor, moment_reduction_factor, pure_force_reduction_factor As Double
    Public limit_value(8), moment_curvature_table(1, 1), moment_force_table(1, 1) As Double
    Public ConfinementFormula(2), TensionFormula(10), confinement_formula, tension_formula, sections(12) As String
    Dim confinment_formulae_num, tension_formulae_num As Integer

    Sub FilFormulaeSB()
        confinment_formulae_num = 2
        ReDim ConfinementFormula(confinment_formulae_num)
        ConfinementFormula(0) = "Suzuki et al. (2004)"
        ConfinementFormula(1) = "Legeron and Paultre (2003)"
        ConfinementFormula(confinment_formulae_num) = "Neglect Confinment"
        tension_formulae_num = 10
        ReDim TensionFormula(tension_formulae_num)
        TensionFormula(0) = "ACI 318"
        TensionFormula(1) = "ACI 363R"
        TensionFormula(2) = "Gardner"
        TensionFormula(3) = "Nihal"
        TensionFormula(4) = "JCI"
        TensionFormula(5) = "JSCE"
        TensionFormula(6) = "CEB-FIB"
        TensionFormula(7) = "Raphael"
```

```
        TensionFormula(8) = "Ahmad and Shah"
        TensionFormula(9) = "Oloukun et al."
        TensionFormula(tension_formulae_num) = "Neglect Tension"
    End Sub
    Function RoundUP(ByVal num As Double, ByVal digit As Integer) As Double
        Dim new_num As Double
        new_num = Math.Round(num, digit)
        If new_num < num Then
            new_num = new_num + 1 / (10 ^ digit)
        End If
        Return new_num
    End Function
    Sub InitialValuesSB()
        FilFormulaeSB()
        section_height = 600 '[mm]
        section_width = 400 '[mm]
        concrete_cover = 20 '[mm]
        E_s = 200000 '[MPa]
        f_cm = 25 '[MPa]
        f_ccm = 50 '[MPa]
        f_cu = 10 '[MPa]
        f_ccu = 20 '[MPa]
        ep_cm = 0.002 '[-]
        ep_ccm = 0.01 '[-]
        ep_cu = 0.0038 '[-]
        ep_cu0 = 1.2 * ep_cu
        ep_ccu = 0.02 '[-]
        f_y = 240 '[MPa]
        f_u = 300 '[MPa]
        f_yt = 240 '[MPa]
        ep_u = 0.2 '[-]
        top_rein_rows_spacing = 100 '[mm]
        bottom_rein_rows_spacing = 100 '[mm]
        layer_thickness = 5 '[mm]
        X_m = 0.1 '[rad/m]
        mio = 0.9 '[-]
        curvatures_iterations = 1000 '[-]
        confined = True
        top_rein_dim = 16 '[mm]
        middle_rein_dim = 10 '[mm]
        bottom_rein_dim = 16 '[mm]
        stirrups_dim = 8 '[mm]
        top_rein_num_per_row = 3 '[bars]
        middle_rein_num_per_row = 2 '[bars] constant
        bottom_rein_num_per_row = 4 '[bars]
        top_rein_rows_num = 1 '[rows]
        middle_rein_rows_num = 2 '[rows]
        bottom_rein_rows_num = 1 '[rows]
        concrete_reduction_factor = 1
        steel_reduction_factor = 1
        stirrups_spacing = 200 '[mm]
        tension_formula = TensionFormula(10)
        confinement_formula = ConfinementFormula(0)
        pure_force_reduction_factor = 1
        interaction_points = 20
    End Sub
    Sub TensileStrengthSB()
        Dim f_spt, k, n, ro As Double
        ro = rein_area / section_area * 100
        If tension_formula = TensionFormula(0) Then
            k = 0.56
```

```
                n = 0.5
            ElseIf tension_formula = TensionFormula(1) Then
                k = 0.59
                n = 0.5
            ElseIf tension_formula = TensionFormula(2) Then
                k = 0.47
                n = 0.59
            ElseIf tension_formula = TensionFormula(3) Then
                k = 0.387
                n = 0.63
            ElseIf tension_formula = TensionFormula(4) Then
                k = 0.13
                n = 0.85
            ElseIf tension_formula = TensionFormula(5) Then
                k = 0.23
                n = 0.67
            ElseIf tension_formula = TensionFormula(6) Then
                k = 0.3
                n = 0.67
            ElseIf tension_formula = TensionFormula(7) Then
                k = 0.313
                n = 0.667
            ElseIf tension_formula = TensionFormula(8) Then
                k = 0.462
                n = 0.55
            ElseIf tension_formula = TensionFormula(9) Then
                k = 0.294
                n = 0.69
            ElseIf tension_formula = TensionFormula(10) Then
                k = 0
                n = 1
            End If
            f_spt = k * f_cm ^ n
            f_ctm = f_spt * 4 / 3
            f_ctu = 0
            ep_ctm = f_ctm / E_c
            If ro < 2 Then
                beta = 32.8 - 27.6 * ro + 7.12 * ro ^ 2
            Else
                beta = 5
            End If
            ep_ctu = beta * ep_ctm
        End Sub
        Sub ResetMomentCurvatureSB()
            max_curvature_point = curvatures_iterations
            TrackBar1.Maximum = max_curvature_point
        End Sub

        Sub ConfiStrenghtSB()
            Dim b_c, d_c, k_e, wi_2, ro_cc, ro_wx, ro_wy, f_scx, f_scy, ro_ex, ro_ey, ro_e, kapa_x, kapa_y As Double
            b_c = section_width - concrete_cover * 2 - stirrups_dim
            d_c = section_height - concrete_cover * 2 - stirrups_dim
            ro_cc = rein_area / b_c / d_c
            ro_wx = (Math.PI * stirrups_dim ^ 2 / 4) * 2 / (stirrups_spacing * b_c)
            ro_wy = (Math.PI * stirrups_dim ^ 2 / 4) * 2 / (stirrups_spacing * d_c)
            wi_2 = (top_rein_num_per_row - 1) * ((b_c - stirrups_dim - top_rein_dim) / (top_rein_num_per_row - 1)) ^ 2
```

```
        wi_2 = wi_2 + (bottom_rein_num_per_row - 1) * ((b_c - stirrups_dim - bottom_rein_dim) / (bottom_rein_num_per_row - 1)) ^ 2
        wi_2 = wi_2 + 2 * (top_rein_rows_num - 1) * top_rein_rows_spacing ^ 2
        wi_2 = wi_2 + 2 * (bottom_rein_rows_num - 1) * bottom_rein_rows_spacing ^ 2
        wi_2 = wi_2 + 2 * (middle_rein_rows_num + 1) * middle_rein_rows_spacing ^ 2
        k_e = ((1 - wi_2 / (6 * b_c * d_c)) * (1 - stirrups_spacing / 2 / b_c) * (1 - stirrups_spacing / 2 / d_c)) / (1 - ro_cc)
        If confinement_formula = ConfinementFormula(0) Then
            f_scx = MinFN(E_s * (0.45 * ep_cm + 0.73 * (k_e * ro_wx / f_cm) ^ 0.7), f_yt)
            f_scy = MinFN(E_s * (0.45 * ep_cm + 0.73 * (k_e * ro_wy / f_cm) ^ 0.7), f_yt)
            ro_ex = k_e * ro_wx * f_scx
            ro_ey = k_e * ro_wy * f_scy
            ro_e = (ro_ex * b_c + ro_ey * d_c) / (b_c + d_c)
            f_ccm = (1 + 4.1 * (ro_e / f_cm) ^ 0.7) * f_cm
            ep_ccm = ep_cm + 0.015 * (ro_e / f_cm) ^ 0.56
            f_ccu = 0.2 * f_ccm
        ElseIf confinement_formula = ConfinementFormula(1) Then
            kapa_x = f_cm / ((k_e * ro_wx) * E_s * ep_cm)
            If kapa_x > 10 Then
                f_scx = MinFN(MaxFN(0.25 * f_cm / ((k_e * ro_wx) * (kapa_x - 10)), 0.43 * ep_cm * E_s), f_yt)
            Else
                f_scx = f_yt
            End If
            kapa_y = f_cm / ((k_e * ro_wy) * E_s * ep_cm)
            If kapa_y > 10 Then
                f_scy = MinFN(MaxFN(0.25 * f_cm / ((k_e * ro_wy) * (kapa_y - 10)), 0.43 * ep_cm * E_s), f_yt)
            Else
                f_scy = f_yt
            End If
            ro_ex = k_e * ro_wx * f_scx
            ro_ey = k_e * ro_wy * f_scy
            ro_e = (ro_ex * b_c + ro_ey * d_c) / (b_c + d_c)
            f_ccm = f_cm * (-1.254 + 2.254 * (1 + 7.94 * ro_e / f_cm) ^ 0.5 - 2 * ro_e / f_cm)
            ep_ccm = ep_cm * (1 + 5 * (f_ccm / f_cm - 1))
            f_ccu = 0.2 * f_ccm
        ElseIf confinement_formula = ConfinementFormula(2) Then
            f_ccm = f_cm
            ep_ccm = ep_cm
            f_ccu = 0.2 * f_ccm
        End If
        E_des = 0.026 * f_cm ^ 3 / ro_e ^ 0.4
        ep_ccu = ep_ccm + 0.8 * f_ccm / E_des
        ep_ccu0 = 1.2 * ep_ccu
            limit_value(1) = ep_cm
            limit_value(2) = ep_cu
            limit_value(3) = ep_ccm
            limit_value(4) = ep_ccu
            limit_value(5) = ep_ctm
            limit_value(6) = ep_ctu
            limit_value(7) = ep_y
            limit_value(8) = ep_u
    End Sub
    Sub ParametersCalcSB()
        Dim k_3 As Double
```

```
            ep_y = f_y / E_s
            E_c = 4730 * (f_cm) ^ 0.5
            k_3 = MinFN(40 / f_cm, 1)
            ep_cm = 0.0028 - 0.0008 * k_3
            ep_cu = MaxFN(0.0078 / f_cm ^ 0.25, ep_cm)
            X_mm = X_m / 1000 '[rad/mm]
            depth_of_first_row_top_rein = concrete_cover + stirrups_dim + top_rein_dim / 2
            depth_of_first_row_bottom_rein = section_height - concrete_cover - stirrups_dim - bottom_rein_dim / 2 - bottom_rein_rows_spacing * (bottom_rein_rows_num - 1)
            middle_rein_rows_spacing = (depth_of_first_row_bottom_rein - depth_of_first_row_top_rein - top_rein_rows_spacing * (top_rein_rows_num - 1)) / (middle_rein_rows_num + 1)
            depth_of_first_row_middle_rein = depth_of_first_row_top_rein + top_rein_rows_spacing * (top_rein_rows_num - 1) + middle_rein_rows_spacing
            depth_of_top_rein = depth_of_first_row_top_rein + top_rein_rows_spacing * (top_rein_rows_num - 1) / 2
            depth_of_bottom_rein = depth_of_first_row_bottom_rein + bottom_rein_rows_spacing * (bottom_rein_rows_num - 1) / 2
            unconfined_layer_thickness = depth_of_first_row_top_rein
            layers_num = Math.Round(section_height / layer_thickness, 0)
            layer_thickness_new = section_height / layers_num
            top_rein_row_area = Math.PI * top_rein_dim ^ 2 / 4 * top_rein_num_per_row
            middle_rein_row_area = Math.PI * middle_rein_dim ^ 2 / 4 * middle_rein_num_per_row
            bottom_rein_row_area = Math.PI * bottom_rein_dim ^ 2 / 4 * bottom_rein_num_per_row
            rein_area = top_rein_row_area * top_rein_rows_num + middle_rein_row_area * middle_rein_rows_num + bottom_rein_row_area * bottom_rein_rows_num
            section_area = section_height * section_width
            applied_force = SectionAxialRsistanceFN(False) * mio
            ConfiStrenghtSB()
            TensileStrengthSB()
        End Sub

        Function ConStressFN(ByVal ep_layer As Double, ByVal confined As Boolean) As Double
            Dim stress, abs_ep As Double
            abs_ep = Math.Abs(ep_layer)
            If ep_layer <= 0 Then
                If confined Then
                    If abs_ep <= ep_ccm Then 'if concrete layer is confined
                        stress = -f_ccm * (1 - (1 - abs_ep / ep_ccm) ^ (E_c * ep_ccm / f_ccm))
                    ElseIf abs_ep <= ep_ccu Then
                        stress = -f_ccm + E_des * (abs_ep - ep_ccm)
                    Else
                        stress = -f_ccu
                    End If
                Else
                    If abs_ep <= ep_cm Then 'if concrete layer is confined
                        stress = -f_cm * (1 - (1 - abs_ep / ep_cm) ^ (E_c * ep_cm / f_cm))
                    ElseIf abs_ep <= ep_cu Then
                        stress = -(f_cm + (f_cu - f_cm) / (ep_cu - ep_cm) * (abs_ep - ep_cm))
                    Else
                        stress = 0
                    End If
                End If
```

```
            Else
                If abs_ep <= ep_ctm Then 'if concrete layer is under tension
                    stress = abs_ep * E_c
                ElseIf abs_ep <= ep_ctu Then
                    stress = 0.625 * f_ctm * (1 - (abs_ep / ep_ctm) / beta + (1 + 0.6 * beta) / (beta * (abs_ep / ep_ctm)))
                Else
                    stress = 0
                End If
            End If
            Return stress * concrete_reduction_factor
        End Function
        Function SteelStressFN(ByVal ep_depth As Double)
            Dim stress, abs_ep As Double
            abs_ep = Math.Abs(ep_depth)
            If abs_ep < ep_y Then
                stress = abs_ep * E_s
            ElseIf abs_ep <= ep_u Then
                stress = (f_u - f_y) / (ep_u - ep_y) * (abs_ep - ep_y) + f_y
            Else
                stress = 0
            End If
            stress = stress * Math.Sign(ep_depth)
            Return stress * steel_reduction_factor
        End Function
        Sub SteelMomentForceSB(ByVal C_s As Double, ByVal X_mm As Double, check As Boolean)
            Dim arm, centroid, ep_steel As Double
            steel_moment = applied_force * section_height / 2
            steel_force = applied_force
            For i = 0 To top_rein_rows_num - 1
                arm = -(C_s - depth_of_first_row_top_rein - top_rein_rows_spacing * i)
                ep_steel = X_mm * arm
                centroid = depth_of_first_row_top_rein + top_rein_rows_spacing * i
                steel_moment = steel_moment + SteelStressFN(ep_steel) * top_rein_row_area * centroid
                steel_force = steel_force + SteelStressFN(ep_steel) * top_rein_row_area
                If check Then
                    For j = 7 To 8
                        If Math.Abs(ep_steel) > limit_value(j) And limit_check(j) = False Then
                            limit_check(j) = True
                        End If
                    Next
                End If
            Next
            For i = 0 To middle_rein_rows_num - 1
                arm = -(C_s - depth_of_first_row_middle_rein - middle_rein_rows_spacing * i)
                centroid = depth_of_first_row_middle_rein + middle_rein_rows_spacing * i
                ep_steel = X_mm * arm
                steel_moment = steel_moment + SteelStressFN(ep_steel) * middle_rein_row_area * centroid
                steel_force = steel_force + SteelStressFN(ep_steel) * middle_rein_row_area
            Next
            For i = 0 To top_rein_rows_num - 1
```

```
                arm = -(C_s - depth_of_first_row_bottom_rein - bottom_rein_rows_spacing * i)
                centroid = depth_of_first_row_bottom_rein + bottom_rein_rows_spacing * i
                ep_steel = X_mm * arm
                steel_moment = steel_moment + SteelStressFN(ep_steel) * bottom_rein_row_area * centroid
                steel_force = steel_force + SteelStressFN(ep_steel) * bottom_rein_row_area
                If check Then
                    For j = 7 To 8
                        If Math.Abs(ep_steel) > limit_value(j) And limit_check(j) = False Then
                            limit_check(j) = True
                        End If
                    Next
                End If
            Next
        End Sub
        Sub ConcMomentForceSB(ByVal C_s As Double, ByVal X_mm As Double, check As Boolean)
            Dim arm, centroid, ep_conc As Double
            conc_moment = 0
            conc_force = 0
            For i = 0 To layers_num - 1
                arm = -(C_s - layer_thickness_new / 2 - layer_thickness_new * i)
                centroid = layer_thickness_new / 2 + layer_thickness_new * i
                ep_conc = X_mm * arm
                If layer_thickness_new / 2 + layer_thickness_new * i < unconfined_layer_thickness Or layer_thickness_new / 2 + layer_thickness_new * i > section_height - unconfined_layer_thickness Then
                    conc_moment = conc_moment + ConStressFN(ep_conc, False) * section_width * layer_thickness_new * centroid
                    conc_force = conc_force + ConStressFN(ep_conc, False) * section_width * layer_thickness_new
                Else
                    conc_moment = conc_moment + ConStressFN(ep_conc, confined) * section_width * layer_thickness_new * centroid
                    conc_force = conc_force + ConStressFN(ep_conc, confined) * section_width * layer_thickness_new
                End If
                If check Then
                    If ep_conc < 0 Then
                        For j = 1 To 4
                            If Math.Abs(ep_conc) > limit_value(j) And limit_check(j) = False Then
                                limit_check(j) = True
                            End If
                        Next
                    Else
                        For j = 5 To 6
                            If Math.Abs(ep_conc) > limit_value(j) And limit_check(j) = False Then
                                limit_check(j) = True
                            End If
                        Next
                    End If
                End If
            Next
        End Sub
        Function FindMomentFN(ByVal X_mm As Double) As Double
```

```
            TabControl1.SelectedTab = TabPage2
            Dim momnet, force, force_up, force_down, depth_up, depth_down As Double
            depth_up = section_height * 0.4
            depth_down = section_height * 0.6
            C_s = depth_up
            SteelMomentForceSB(C_s, X_mm, False)
            ConcMomentForceSB(C_s, X_mm, False)
            force_up = -steel_force - conc_force
            C_s = depth_down
            SteelMomentForceSB(C_s, X_mm, False)
            ConcMomentForceSB(C_s, X_mm, False)
            force_down = -steel_force - conc_force
            Dim max_i As Integer = 1000
            For i = 1 To max_i
                C_s = (-force_up) * (depth_down - depth_up) / (force_down - force_up) + depth_up
                If Math.Abs(C_s) > section_height * 10 ^ 6 Then
                    C_s = section_height * 10 ^ 3
                ElseIf C_s < 0 Then
                    C_s = 0.1
                End If
                SteelMomentForceSB(C_s, X_mm, False)
                ConcMomentForceSB(C_s, X_mm, False)
                momnet = steel_moment + conc_moment
                force = steel_force + conc_force
                If Math.Round(force, 3) = 0 Then
                    i = max_i + 1
                Else
                    If force < 0 Then
                        force_up = -force
                        depth_up = C_s
                    ElseIf force > 0 Then
                        force_down = -force
                        depth_down = C_s
                    End If
                End If
            Next
            SteelMomentForceSB(C_s, X_mm, True)
            ConcMomentForceSB(C_s, X_mm, True)
            Return momnet
        End Function
        Function SectionAxialRsistanceFN(ByVal confined As Boolean) As Double
            Dim resistance, core_height, core_width, core_area As Double
            If confined Then
                core_height = section_height - 2 * unconfined_layer_thickness
                core_width = section_width - 2 * unconfined_layer_thickness
                core_area = core_height * core_width
                resistance = rein_area * f_y + (core_area - rein_area) * f_ccm + (section_area - core_area) * f_cm
            Else
                resistance = rein_area * f_y + (section_area - rein_area) * f_cm
            End If

            Return resistance
        End Function

        Sub MomentCurvatureSB()
            ReDim moment_curvature_table(3, curvatures_iterations + 10)
            Dim X_mm_i As Double
            ResetSB()
```

```
            X_mm_i = X_mm / curvatures_iterations
            max_momnet_value = 0
            max_moment_piont = 0
            ProgressBar1.Value = 0
            For i = 1 To curvatures_iterations
                moment_curvature_table(1, i) = X_mm_i * i
            Next
            Dim close As Boolean = False
            For i = 1 To curvatures_iterations
                ProgressBar1.Value = ProgressBar1.Value + ProgressBar1.Maximum / curvatures_iterations
                moment_curvature_table(2, i) = FindMomentFN(X_mm_i * i)
                moment_curvature_table(3, i) = C_s

                If moment_curvature_table(2, i) > max_momnet_value And (Math.Round(moment_curvature_table(2, i)) > Math.Round(moment_curvature_table(2, i - 1)) * 5) = False Then
                    max_momnet_value = moment_curvature_table(2, i)
                    max_moment_piont = i
                End If
                If Math.Round(moment_curvature_table(2, i) / 1000) = 0 And moment_curvature_table(1, i) <> 0 Then
                    max_curvature_point = i
                    close = True
                End If
                For j = 1 To 8
                Next
                If close Then
                    i = curvatures_iterations + 1
                End If
            Next
        End Sub
        Function MinFN(a As Double, b As Double)
            If a < b Then
                Return a
            Else
                Return b
            End If
        End Function
        Function MaxFN(a As Double, b As Double)
            If a > b Then
                Return a
            Else
                Return b
            End If
        End Function
        Sub MomentCuruatureTableSB()
            DataGridView1.Rows.Clear()
            DataGridView1.ColumnCount = 3
            DataGridView1.Columns(0).Name = "Curvature [1/m]"
            DataGridView1.Columns(1).Name = "Bending Moment [kN.m]"
            DataGridView1.Columns(2).Name = "Cs [mm]"
            DataGridView1.AutoSizeColumnsMode() = DataGridViewAutoSizeColumnsMode.Fill
            Dim row As String()
            For i = 1 To max_curvature_point
                row = New String() {moment_curvature_table(1, i) * 1000, Math.Round(moment_curvature_table(2, i) / 10 ^ 6, 0), Math.Round(moment_curvature_table(3, i))}
                DataGridView1.Rows.Add(row)
            Next
        End Sub
```

```
        Private Sub DrawChart(theChart As Chart)
            Dim theFontsizex As Integer = CInt(theChart.ClientSize.Width / 60)
            'setup the chart
            With theChart.ChartAreas(0)
                .AxisX.Title = "Curvature [1/m]"
                .AxisX.TitleFont = New Font("Times New Roman", CInt(theFontsizex * 1.2), FontStyle.Bold)
                .AxisX.MajorGrid.LineColor = Color.LightBlue
                .AxisX.Minimum = 0
                .AxisX.LabelStyle.Font = New Font("Arial", theFontsizex)
                .AxisX.IsLabelAutoFit = False
                .AxisY.Title = "Moment [kN.m]"
                .AxisY.TitleFont = New Font("Times New Roman", CInt(theFontsizex * 1.2), FontStyle.Bold)
                .AxisY.MajorGrid.LineColor = Color.LightGray
                .AxisY.Minimum = 0
                .AxisY.LabelStyle.Font = New Font("Arial", theFontsizex)
                .AxisY.IsLabelAutoFit = False
                .BackColor = Color.FloralWhite
                .BackSecondaryColor = Color.White
                .BackGradientStyle = GradientStyle.HorizontalCenter
                .BorderColor = Color.Blue
                .BorderDashStyle = ChartDashStyle.Solid
                .BorderWidth = 1
                .ShadowOffset = 2
            End With
            DrawCurveSB(max_moment_piont)
        End Sub
        Sub DrawCurveSB(mark As Integer)
            'draw the chart
            Chart1.Series.Clear()
            Chart1.Series.Add("Y = f(x)")
            With Chart1.Series(0)
                .ChartType = DataVisualization.Charting.SeriesChartType.Line
                .BorderWidth = CInt(Chart1.ClientSize.Width / 400)
                .Color = Color.Red
                .IsVisibleInLegend = False

                Dim y As Single
                For i = 0 To curvatures_iterations Step 1
                    y = Math.Abs(Math.Round(moment_curvature_table(2, i) / 10 ^ 6, 3))
                    .Points.AddXY(moment_curvature_table(1, i) * 1000, y)
                Next
            End With
            Chart1.Series.Add("Point")
            With Chart1.Series("Point")
                .IsVisibleInLegend = False
                .ChartType = DataVisualization.Charting.SeriesChartType.Point
                .MarkerStyle = MarkerStyle.Circle
                .MarkerSize = 7
                .MarkerColor = Color.BlueViolet
                .Points.AddXY(moment_curvature_table(1, mark) * 1000, moment_curvature_table(2, mark) / 10 ^ 6)
            End With
        End Sub
        Sub MomentCurvatureGraphSB()
            DrawChart(Chart1)
        End Sub

```

```
        Private Sub SectionToolStripMenuItem_Click(sender As Object, e As EventArgs) Handles SectionToolStripMenuItem.Click
            DefineSection.Show()
        End Sub
        Private Sub MaterialsToolStripMenuItem_Click(sender As Object, e As EventArgs) Handles MaterialsToolStripMenuItem.Click
            DefineMaterials.Show()
        End Sub
        Sub DuctilityTextSB()
            LabelForce.Text = "Axial Force Capacity: " & Math.Round(SectionAxialRsistanceFN(False) / 1000) & " kN," & vbNewLine & "Maximum Moment: " & Math.Round(max_momnet_value / 10 ^ 6) & " kN.m, Curvature: " & moment_curvature_table(1, max_moment_piont) * 1000 & " 1/m"
            If limit_check(7) And limit_check(2) Then
                LabelForce.Text = LabelForce.Text & vbNewLine & "Yielding Curvature: " & moment_curvature_table(1, limit_iteration(7)) * 1000 & " 1/m" & vbNewLine & "Ultimate Curvature: " & moment_curvature_table(1, limit_iteration(2)) * 1000 & " 1/m" & vbNewLine & "Ductility: " & Math.Round(moment_curvature_table(1, limit_iteration(2)) / moment_curvature_table(1, limit_iteration(7)), 2)
            End If
        End Sub
        Private Sub MomentCurvatureToolStripMenuItem_Click(sender As Object, e As EventArgs) Handles MomentCurvatureToolStripMenuItem.Click
            GetBoxesSB()
            interaction = False
            ParametersCalcSB()
            MomentCurvatureSB()
            MomentCuruatureTableSB()
            MomentCurvatureGraphSB()
            ResetMomentCurvatureSB()
            TrackBar1.Value = max_moment_piont
            DuctilityTextSB()
            SetVisibilitySB(False)
        End Sub
        Private Sub MainForm_Load(sender As Object, e As EventArgs) Handles MyBase.Load
            InitialValuesSB()
            ParametersCalcSB()
            FillBoxesSB()
        End Sub
        Private Sub TrackBar1_Scroll(sender As Object, e As EventArgs) Handles TrackBar1.Scroll
            Dim i As Integer = TrackBar1.Value
            If interaction Then
                DrawCurveMomentForceSB(i)
            Else
                DrawCurveSB(i)
                RadioButton10.Checked = True
            End If
            TextSB(i)
        End Sub
        Sub TextSB(i As Integer)
            If interaction Then
                LabelPiont1.Text = "Applied Force: " & Math.Round(moment_force_table(1, i) / 1000) & " kN"
                LabelPiont2.Text = "Moment Resistance: " & Math.Round(moment_force_table(2, i) / 10 ^ 6) & " kN/m"
            Else
                LabelPiont1.Text = "Curvature: " & moment_curvature_table(1, i) * 1000 & " 1/m"
```

```
                LabelPiont2.Text = "Moment: " & Math.Round(moment_curvature_table(2, i) / 10 ^ 6) & " kN/m"
            End If
        End Sub
        Private Sub ConcreteStressStrainToolStripMenuItem_Click(sender As Object, e As EventArgs) Handles ConcreteStressStrainToolStripMenuItem.Click
            ConfinedConcreteStressStrain.Show()
        End Sub
        Private Sub UnconfinedConcreteStressStrainToolStripMenuItem_Click(sender As Object, e As EventArgs) Handles UnconfinedConcreteStressStrainToolStripMenuItem.Click
            UnconfinedConcreteStressStrain.Show()
        End Sub
        Private Sub SteelSressStrainToolStripMenuItem_Click(sender As Object, e As EventArgs) Handles SteelSressStrainToolStripMenuItem.Click
            SteelBarsStressStrain.Show()
        End Sub
        Sub LimitsTableSB()
            DataGridView1.ColumnCount = 3
            DataGridView1.Columns(0).Name = "Curvature [1/m]"
            DataGridView1.Columns(1).Name = "Bending Moment [kN.m]"
            DataGridView1.Columns(2).Name = "Cs [mm]"
            DataGridView1.AutoSizeColumnsMode() = DataGridViewAutoSizeColumnsMode.Fill
            Dim row As String()
            For i = 1 To max_curvature_point
                row = New String() {moment_curvature_table(1, i) * 1000, Math.Round(moment_curvature_table(2, i) / 10 ^ 6, 0), Math.Round(moment_curvature_table(3, i))}
                DataGridView1.Rows.Add(row)
            Next
        End Sub
        Private Sub RadioButton1_CheckedChanged(sender As Object, e As EventArgs) Handles RadioButton1.CheckedChanged
            Try
                DrawCurveSB(limit_iteration(1))
                TrackBar1.Value = limit_iteration(1)
                TextSB(limit_iteration(1))
            Catch ex As Exception
            End Try
        End Sub
        Private Sub RadioButton2_CheckedChanged(sender As Object, e As EventArgs) Handles RadioButton2.CheckedChanged
            Try
                DrawCurveSB(limit_iteration(2))
                TrackBar1.Value = limit_iteration(2)
                TextSB(limit_iteration(2))
            Catch ex As Exception
            End Try
        End Sub
        Private Sub RadioButton3_CheckedChanged(sender As Object, e As EventArgs) Handles RadioButton3.CheckedChanged
            Try
                DrawCurveSB(limit_iteration(3))
                TrackBar1.Value = limit_iteration(3)
                TextSB(limit_iteration(3))
            Catch ex As Exception

            End Try
        End Sub
        Private Sub RadioButton4_CheckedChanged(sender As Object, e As EventArgs) Handles RadioButton4.CheckedChanged
            Try
```

```
                DrawCurveSB(limit_iteration(4))
                TrackBar1.Value = limit_iteration(4)
                TextSB(limit_iteration(4))
            Catch ex As Exception
            End Try
        End Sub
        Private Sub RadioButton5_CheckedChanged(sender As Object, e As EventArgs) Handles RadioButton5.CheckedChanged
            Try
                DrawCurveSB(limit_iteration(5))
                TrackBar1.Value = limit_iteration(5)
                TextSB(limit_iteration(5))
            Catch ex As Exception

            End Try
        End Sub
        Private Sub RadioButton6_CheckedChanged(sender As Object, e As EventArgs) Handles RadioButton6.CheckedChanged
            Try
                DrawCurveSB(limit_iteration(6))
                TrackBar1.Value = limit_iteration(6)
                TextSB(limit_iteration(6))
            Catch ex As Exception
            End Try
        End Sub
        Private Sub RadioButton7_CheckedChanged(sender As Object, e As EventArgs) Handles RadioButton7.CheckedChanged
            Try
                DrawCurveSB(limit_iteration(7))
                TrackBar1.Value = limit_iteration(7)
                TextSB(limit_iteration(7))
            Catch ex As Exception

            End Try
        End Sub
        Private Sub RadioButton8_CheckedChanged(sender As Object, e As EventArgs) Handles RadioButton8.CheckedChanged
            Try
                DrawCurveSB(limit_iteration(8))
                TrackBar1.Value = limit_iteration(8)
                TextSB(limit_iteration(8))
            Catch ex As Exception
            End Try
        End Sub
        Private Sub TensileConcreteStressStrainToolStripMenuItem_Click(sender As Object, e As EventArgs) Handles TensileConcreteStressStrainToolStripMenuItem.Click
            TensileConcreteStressStrain.Show()
        End Sub
        Sub MomentForceSB()
            Dim mio_i As Double
            max_moment_force_value = 0
            max_moment_force_piont = 0
            ReDim moment_force_table(3, interaction_points)
            For i = 0 To interaction_points - 1
                If pure_force_reduction_factor < 1 Then
                    mio_i = i / (interaction_points - 1) * pure_force_reduction_factor
                Else
                    mio_i = i / interaction_points
                End If
                applied_force = mio_i * SectionAxialRsistanceFN(False)
```

```
                MomentCurvatureSB()
                If max_momnet_value = 0 Then
                    moment_force_table(2, i) = moment_force_table(2, i - 1)
                    moment_force_table(1, i) = moment_force_table(1, i - 1)
                    moment_force_table(3, i) = moment_force_table(3, i - 1)
                Else
                    moment_force_table(2, i) = max_momnet_value
                    moment_force_table(1, i) = applied_force
                    moment_force_table(3, i) = mio_i * 100
                End If
                If max_moment_force_value < max_momnet_value Then
                    max_moment_force_value = max_momnet_value
                    max_moment_force_piont = i
                End If
            Next
            moment_force_table(2, interaction_points) = 0
            moment_force_table(1, interaction_points) = SectionAxialRsistanceFN(False) * pure_force_reduction_factor
            moment_force_table(3, interaction_points) = 100 * pure_force_reduction_factor
        End Sub
        Sub MomentForceTableSB()
            DataGridView1.Rows.Clear()
            DataGridView1.ColumnCount = 3
            DataGridView1.Columns(0).Name = "Force [kN]"
            DataGridView1.Columns(1).Name = "Bending Moment [kN.m]"
            DataGridView1.Columns(2).Name = "μ [%]"
            DataGridView1.AutoSizeColumnsMode() = DataGridViewAutoSizeColumnsMode.Fill
            Dim row As String()
            For i = 0 To interaction_points
                row = New String() {Math.Round(moment_force_table(1, i) / 1000, 0), Math.Round(moment_force_table(2, i) / 10 ^ 6, 0), Math.Round(moment_force_table(3, i))}

                DataGridView1.Rows.Add(row)
            Next
        End Sub
        Sub MomentForceGraphSB()
        End Sub
        Private Sub InteractionCurveToolStripMenuItem_Click(sender As Object, e As EventArgs) Handles InteractionCurveToolStripMenuItem.Click
            GetBoxesSB()
            interaction = True
            ParametersCalcSB()
            MomentForceSB()
            MomentForceTableSB()
            DrawChartMomentForceSB(Chart1)
            TrackBar1.Maximum = interaction_points
            TrackBar1.Value = max_moment_force_piont
            SetVisibilitySB(True)
        End Sub
        Private Sub DrawChartMomentForceSB(theChart As Chart)
            Dim theFontsizex As Integer = CInt(theChart.ClientSize.Width / 60)
            'setup the chart
            With theChart.ChartAreas(0)
                .AxisX.Title = "Moment [kN.m]"
                .AxisX.TitleFont = New Font("Times New Roman", CInt(theFontsizex * 1.2), FontStyle.Bold)
                .AxisX.MajorGrid.LineColor = Color.LightBlue
                .AxisX.Minimum = 0
                .AxisX.LabelStyle.Font = New Font("Arial", theFontsizex)
```

```
            .AxisX.IsLabelAutoFit = False
            .AxisY.Title = "Force [kN]"
            .AxisY.TitleFont = New Font("Times New Roman", CInt(theFontsizex * 1.2), FontStyle.Bold)
            .AxisY.MajorGrid.LineColor = Color.LightGray
            .AxisY.Minimum = 0
            .AxisY.LabelStyle.Font = New Font("Arial", theFontsizex)
            .AxisY.IsLabelAutoFit = False
            .BackColor = Color.FloralWhite
            .BackSecondaryColor = Color.White
            .BackGradientStyle = GradientStyle.HorizontalCenter
            .BorderColor = Color.Blue
            .BorderDashStyle = ChartDashStyle.Solid
            .BorderWidth = 1
            .ShadowOffset = 2
        End With
        DrawCurveMomentForceSB(max_moment_force_piont)
    End Sub
    Sub DrawCurveMomentForceSB(mark As Integer)
        'draw the chart
        Chart1.Series.Clear()
        Chart1.Series.Add("Y = f(x)")
        With Chart1.Series(0)
            .ChartType = DataVisualization.Charting.SeriesChartType.Line
            .BorderWidth = CInt(Chart1.ClientSize.Width / 400)
            .Color = Color.Red
            .IsVisibleInLegend = False
            Dim y As Single
            For i = 0 To interaction_points Step 1
                .Points.AddXY(moment_force_table(2, i) / 10 ^ 6, moment_force_table(1, i) / 1000)
            Next
        End With
        Chart1.Series.Add("Point")
        With Chart1.Series("Point")
            .IsVisibleInLegend = False
            .ChartType = DataVisualization.Charting.SeriesChartType.Point
            .MarkerStyle = MarkerStyle.Circle
            .MarkerSize = 7
            .MarkerColor = Color.BlueViolet
            .Points.AddXY(moment_force_table(2, mark) / 10 ^ 6, moment_force_table(1, mark) / 1000)
        End With
    End Sub
    Private Sub ExitToolStripMenuItem_Click(sender As Object, e As EventArgs) Handles ExitToolStripMenuItem.Click
        Me.Close()
    End Sub

    Private Sub TextBox3_TextChanged(sender As Object, e As EventArgs) Handles TextBox3.TextChanged
        Try
            TextBox6.Text = Math.Round(TextBox3.Text * SectionAxialRsistanceFN(False) / 1000)
        Catch ex As Exception
        End Try
    End Sub
    Private Sub RadioButton9_CheckedChanged(sender As Object, e As EventArgs) Handles RadioButton9.CheckedChanged
        Try
            DrawCurveSB(max_moment_piont)
```

```
                TrackBar1.Value = max_moment_piont
                TextSB(max_moment_piont)
            Catch ex As Exception
            End Try
        End Sub
    End Class
```