

**Comparison between Nonlinear Analysis and ACI
Simplified Effective Stiffness Analysis Methods for
Reinforced Concrete Frames Under Lateral Load**

مقارنة استخدام التحليل الخطي وطريقة التحليل المبسطة للجساءة عند تحليل
الاطارات الخرسانية المعرضة للأحمال الجانبية

by

HAJER MUSTAFA IBRAHIM ELMUTASHY

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ABSTRACT

When reinforced concrete frames subjected to lateral load manifesting in inelastic damage in the form of cracks that diminish the structural element's stiffness. Evaluating this damage often employs non-linear analysis, yet simplified methods prescribed by international codes and numerous studies estimate the effective stiffness of these elements are used for elastic linear analysis. The accurate estimation of effective stiffness is crucial as it profoundly impacts the overall structural performance. This research endeavors to compare the non-linear performance of the structure with the linear performance using the assumptions proposed by ACI-318-19, permitting the use of $0.7EI_g$ and $0.35EI_g$ as effective stiffness values for columns and beams, respectively. To achieve this, 66 one-bay one-story frames are modelled and subjected to non-linear static analysis using ETABS software. The model parameters encompass compressive strength, reinforcement ratios, column height and axial load. The analysis presents load-deflection characteristics for the entire frame which used to calculate the effective stiffness. Results subjected to statistical analysis which indicate that increasing compressive strength augments structural stiffness, whereas heightened axial load and frame height notably diminish stiffness. Conversely, employing the non-linear analysis method result in higher effective stiffness than simplified method by mean value of 1.36, 1.44 and 1.57 for frames with compressive strength 40,80 and 120mpa respectively.

Keywords: effective stiffness, static nonlinear analysis, simplified stiffness method

الخلاصة

عند تعرض الاطارات الخرسانية المسلحة الي احمال جانبيه فانها تتضرر بشكل غير خطي حيث تتكون تشققات دائمه وتؤثر هذه التشققات في التقليل من صلابة العناصر الانشائية الاخرسانية للاطار. غالبا في التحليل الانشائي للاطارات يستخدم التحليل الخطي وتقدر قيم الصلابه لهذه العناصر باستخدام طرق مبسطه منصوص عليها في الرموز الدوليه والعديد من الدراسات . يعد التقدير الدقيق للصلابه الفعاله امر بالغ الاهميه لانه يؤثر بشكل بالغ علي اداء المنشأ الخرساني . هذا البحث يهدف الي مقارنة الأداء الغير خطي للمنشأ بالاداء الخطي مستخدما قيم الافتراضات التي وضعها (**ACI-318-19**) حيث سمح باستخدام قيم الجسء 0.7 من القيمه الكليه لجسءة العمود و 0.35 من القيمه الكليه لجسءة العوارض. لتحقيق ذلك, تم تمثيل عدد 66 اطار من طابق واحد وعارضه واحده وتم تحليلها تحليل غير خطي مع اعتبار تعريضها لخصائص مختلفه وتتمثل في مقاومة الضغط للخرسانه, نسبة تسليح الاعمده, الحمل المحوري وارتفاع الطابق (العمود). ينتج من التحليل منحي القوي-الانحراف الجانبي ليمثل اداء المنشأ الخرسانيه وتحسب منه قيم الجسءة الفعاله. اوضحت النتائج أن زيادة مقاومة الخرسانه للضغط تزيد من جسءة المنشأ بيما زيادة كل من الحمل المحوري وارتفاع العمود يقلل جدا من جسءة المبنى كما أثبتت النتائج أن طريقة التحليل الغير خطي تنتج عنها قيم جسءه أكبر من استخدم الطرق المبسطه بي قيم 1.36, 1.44 و 1.57 للاطارات الخرسانيه التي تمتاز بمقاومة خرسانه 40, 80 و 120 ميجا باسكال علي التوالي.

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Table of contents

Chapter 1: Introduction	1
1.1 Background to the Study.....	1
1.2 Problem Statement.....	3
1.3 Objectives of the Study.....	3
1.4 Preliminary Literature Review.....	4
1.5 Methodology.....	6
1.6 Research Significance.....	7
Chapter 2: Literature Review	8
2.1 Introduction	8
2.2 Effective Stiffness for Concrete Building	8
2.3 Effective Stiffness Influence on Structural Analysis and Design.....	10
2.3.1 P-delta (P- Δ) Effect	10
2.3.2 The Distribution of the Internal Forces	11
2.3.3 Influence of the Effective Stiffness on Dynamic Analysis	12
2.4 Existing Effective Stiffness Models (Simplified Methods for Estimating Effective Stiffness)	12
2.5 Effective Stiffness Parameters.....	20
2.5.1 The Influence of the Reinforcement Ratio.....	21
2.5.2 The Influence of the Compressive Strength.....	21
2.5.3 Member Length	22
2.5.4 Axial Load.....	23

2.6	Reinforced Concrete Non-Linearity	23
2.6.1	Material Non-Linearity	23
2.6.2	Geometrical Non-Linearity	31
2.7	Static Linear Analysis.....	35
2.7.1	What is Linear Static Analysing?.....	35
2.7.2	Limitation of Static Linear Analysis	36
2.8	Non-Linear Static Procedure (Pushover Analysis).....	37
2.8.1	The Advantages of the Pushover Analysis.....	38
2.8.2	The Disadvantages of Push Over Analysis	39
2.8.3	Pushover and Structural Stiffness	39
2.8.4	Structural Performance Level.....	41
Chapter 3:	Methodology.....	44
3.1	Introduction	44
3.2	Research Philosophy.....	44
3.3	Research Approach.....	44
3.4	Research Design	45
3.5	Modelling and Analysis.....	48
3.6	Limitation of Study.....	50
Chapter 4:	Results and Discussion.....	51
4.1	The Influence of the Study Parameters on the Structural Performance	51
4.1.1	Reinforcement Ratio	51

4.1.2	Compressive Strength	53
4.1.3	Column Height	55
4.1.4	Axial Load Effect	56
4.2	The Comparison Between the Performance of Structure Using Simplified and Non-Linear Analysis Method of Flexural Stiffness Estimation	57
Chapter 5: Conclusion and Recommendation.....		62
5.1	Conclusion.....	62
5.1.1	The Influence of the Study Parameters on the Structural Performance	62
5.1.2	The Comparison Between the Performance of Structure Using Simplified and Non-Linear Analysis Method of Flexural Stiffness Estimation	63
5.2	Recommendation.....	63
References		64
Appendices.....		68

List of Tables

Table 1: Existing Effective Stiffness Models Expressing the Affected Parameters	19
Table 2: Existing Stress-Strain Behaviour of Concrete Under Compression	24
Table 3: The Influence of the Columns Height on the Frame Performance	55
Table 4: Descriptive Statistics for the Two Analysis Methods.....	58

List of Figures

Figure 1: Behavior of Reinforced Concrete Element in Flexure: (A) Member Subjected to Lateral Load; (B) Moment-Curvature Response; (C) Load-Deflection Response	2
Figure 2: Definition of Yield Displacement and Effective Stiffness from (Berry Et Al.2004) Test Data for: (a) Yielding Columns; and (b) Columns that did not Yield	16
Figure 3: Comparison of Different Effective Stiffness Models with Analytical and Experimental Estimates for Normal and High Strength Concrete.	17
Figure 4: (Carreira & Chu, 1985) Stress-Strain Concrete Tension Model.....	30
Figure 5: Stress-Strain Tensile Model.....	31
Figure 6: Column P-Delta effect: Compressive and Lateral Forces Acting Simultaneously	33
Figure 7: Idealized Static Pushover Backbone Curve (Fema 2005)	40
Figure 8: Performance Levels of Structure	42
Figure 9: Research Concrete Frame Model.....	46
Figure 10: Effective Stiffness Calculation Method.....	47
Figure 11: The Influence of Reinforcement Ratio on Structure Performance Lateral Stiffness (a) $f_c=40\text{mpa}$, (b) $f_c=80\text{mpa}$, (c) $f_c=120\text{mpa}$	52
Figure 12: The Influence of Compressive Strength on Lateral Stiffness. (a) Frame height = 4m, (b) frame height = 5m	54
Figure 13: Axial Load Effect on Lateral Stiffness	57
Figure 14: Lateral Stiffness Results Based on Simplified and Non-Linear Analysis Methods (a) frame height = 4m, (b) frame height =5m	61

Chapter 1: Introduction

1.1 Background to the Study

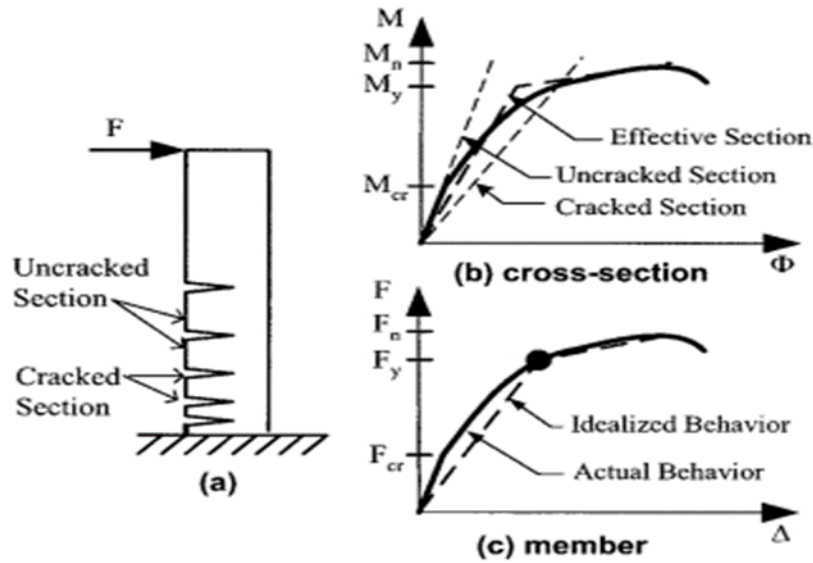
In concrete frame buildings, with the presence of lateral loads concrete element subjected to severe cracks. these cracks taking elastic behaviour until the reinforced concrete material reach the yield point then inelastic cracks begin to form and result in affecting the characteristics of each element. This impact manifests in alterations to both the moment of inertia and the cross-sectional area (flexural stiffness) and reduced it. See fig (1). Which can be expressed as flexural effective stiffness

In order to capture the structure behaviour in this case non-linear analysis is required to cover both material and geometric nonlinearity, Consequently, codes in general and the ACI 318-19 Building code in specific provide simplified estimation of the effective stiffness to be adopted with the using of linear elastic analysis by addressing these changes by offering estimations of the EI value (representing flexural stiffness) in Table 6.6.3.1.1(a). This table includes reduced values for both the moment of inertia and the cross-sectional area, permitting elastic analysis at the factor load level.

Specifically, the table suggests using the full cross-sectional area ($1.0 A_g$), while the moment of inertia is advised to be reduced to $0.7I_g$, with a further reduction to $0.35I_g$ for columns and beams, respectively. Additionally, within the same code, table 6.6.3.1.1(b) provides alternative equations for calculating moments of inertia to facilitate elastic analysis under factored loads. These equations rely on various parameters specific to the elements being analysed. However, it's important to note that certain restrictions apply to the I_g value. For columns, the I_g value should not fall below $0.35I_g$ nor exceed $0.815I_g$. Similarly, for beams, the acceptable range for I_g is defined with a minimum value of $0.25I_g$ and a maximum value that needs to be determined.

Figure 1

Behavior of Reinforced Concrete Element in Flexure: (A) Member Subjected to Lateral Load; (B) Moment-Curvature Response; (C) Load-Deflection Response



Note. (Mehanny Et. Al 2001)

Reducing the flexural stiffness of concrete sections during design analysis can significantly escalate the overall cost of structures. Despite this, prioritizing safety requirements remains a paramount concern in structural engineering, consistently outweighing mere economic considerations. Nevertheless, reducing economic costs concurrently serves the greater goal of sustainability.

Conversely, overestimating the actual stiffness leads to unrealistic predictions concerning the structure's performance, especially under lateral loads. This overestimation undermines the fundamental principle of safe design. Therefore, delving into the realistic assessment of flexural stiffness becomes crucial. Striking a balance between achieving structural safety while considering economic and sustainability aspects becomes imperative in the realm of structural design.

1.2 Problem Statement

ACI-318-19 code, permit the estimation of effective flexural stiffness in reinforced concrete elements as a percentage of their actual stiffness, disregarding specific characteristics like reinforcement ratio or compressive strength. However, the precision in determining this realistic effective stiffness directly impacts the overall performance of the structure, thereby influencing both safety and the economic aspects of the design.

Hence, the critical research questions emerge: What disparities arise from employing simplified methods to gauge effective flexural stiffness rather than relying on actual values obtained through rigorous analysis? How does the adoption of these simplified methods impact the performance of the structure? Should substantial differences manifest, what parameter or parameters contribute to these discrepancies? Finally, can statistical non-linear analysis sufficiently capture and comprehend the structural performance?

Analysing the divergence between simplified estimations and rigorous analysis in determining effective flexural stiffness holds significance, as it bears on the structural integrity, safety considerations, and the financial facets of design. Understanding whether simplified approaches adequately represent the structural behaviour or if they fall short in capturing vital nuances becomes pivotal in ensuring accurate and reliable structural design methodologies.

1.3 Objectives of the Study

This research aims to delve into the realistic of the moment of inertia (I_g) for concrete frames experiencing lateral loads. The primary focus is to compare the commonly employed simplified method widely used by structure engineers, as outlined in the (Building Code Requirements for Structural Concrete (ACI 318-19 assuming the value of $.7EI_g$ for columns and $0.35EI$ for beams. The specific objectives guiding this investigation can be delineated as follows:

1- Identify and study the affected parameters that influence the flexural stiffness of reinforce concrete elements.

2- Compare the performance of the structure for using the simplified method for estimating flexural stiffness with the performance using nonlinear analysis.

This research aims to offer insights that transcend the simplified approach's surface-level estimations, aiming to enhance the accuracy and reliability of moment of inertia evaluations in concrete frames subjected to lateral loads.

1.4 Preliminary Literature Review

Many studies in the literature were seek to provide an accurate model that can express the flexural stiffness of reinforced concrete frames, most of them were based on the axial loads which adopted by professional codes (ACI-318-19) (ASCE-41) (FEMA).

Some of suggested model are calculated as a percentage of the moment of inertia for example beams effective stiffness is computed as $EI_{eff} = 0.35 EI_g$. other models are proposed as equations using different parameters to calculate the effective stiffness.

Number of parameters were considered in each study including, compressive strength, reinforcement ratios, eccentricity for columns (M/PH), member length and etc. where the using of inaccurate effective stiffness claimed to be led to in accurate performance which result in poor analysis and design.

Concrete structures demonstrate complex nonlinear characteristics, stemming from both material composition and structural shape, pivotal factors influencing how concrete structures perform and react in structural engineering. Material nonlinearity denotes the deviation from a linear stress-strain relationship, a trait evident in concrete due to its diverse mix of aggregates, cement, water, and additives. Initially, concrete behaves linearly until it reaches a stress threshold, after which it toughens, displaying greater rigidity. However, prolonged exposure to high stress triggers strain-softening in concrete, causing a

decrease in stiffness and the formation of micro-cracks, ultimately leading to diminished load-bearing capacity and potential structural failure.

Geometrical non-linear behaviour pertains to alterations in a structure's form or arrangement during deformation. In the case of concrete structures, substantial loads or seismic forces can induce considerable deformations, resulting in geometric non-linearity. This encompasses phenomena like P-delta effects, where axial and lateral forces create extra moments, as well as substantial displacements that alter the structure's stiffness and redistribute internal forces.

Comprehending these non-linear tendencies within concrete is essential for precise structural analysis and design. Engineers leverage sophisticated modelling methods and software to replicate and anticipate the intricate non-linear reactions of concrete structures. This empowers the development of safer, more robust designs, accounting for the material and geometric complexities influencing concrete's behaviour under diverse loading circumstances, such as employing non-linear analysis methods like static non-linear analysis.

Static non-linear analysis, also known as Pushover analysis, stands as an advanced technique in structural engineering employed to evaluate how buildings and similar structures fare under seismic loads. In contrast to conventional linear approaches, Pushover analysis takes into account non-linear behaviour to replicate how a structure reacts to gradually intensifying lateral forces, mirroring the impact of seismic events. This method involves assessing the structure's response by progressively pushing it past its elastic threshold until it approaches collapse or substantial deformation. Engineers rely on specialized software to simulate the structure's behaviour, factoring in elements such as material characteristics, geometry, and connection specifics.

The assessment produces a "pushover curve" depicting how the structure's displacement relates to the applied force, providing crucial understanding of its performance in seismic scenarios. This data serves multiple purposes: refining design, confirming adherence to safety regulations, and facilitating informed choices regarding reinforcing or retrofitting current structures. Ultimately, pushover analysis is a potent instrument in seismic design, enabling the evaluation and improvement of structures' resistance to earthquakes, thereby bolstering the safety and resilience of buildings.

1.5 Methodology

The primary objective of this research is to conduct a meticulous and comprehensive non-linear analysis of a varied range of concrete frames. The investigation will encompass an array of parameters acknowledged to significantly impact flexural stiffness. This study will take into account diverse reinforcement ratios, concrete compressive strengths, and varying frame heights across a spectrum of axial load values.

Averaging the remarkable success of finite element analysis methods since the 1970s, the research methodology hinges on the utilization of ETABS software. ETABS has been deliberately selected to simulate multiple concrete frames, employing non-linear static analysis, specifically the pushover method, to model sway frames. The choice of employing non-linear static analysis methodology is justified by its established efficacy in replicating frame behaviour under extreme lateral loads, notably seismic loads. Moreover, ETABS demonstrates the capability to accurately simulate the intricate non-linear characteristics inherent in concrete structures.

The ensuing analysis will subject the obtained results to rigorous statistical analysis. This statistical analysis aims to discern and elucidate the individual effects of each parameter on structural performance. Additionally, it seeks to appraise disparities

between employing simplified analysis methods and the more intricate non-linear analysis approach.

By undertaking this detailed research methodology, the study endeavors to contribute comprehensive insights into the influence of distinct parameters on structural behaviour. This comprehensive approach is imperative in advancing the understanding of structural dynamics and informing more refined and robust design practices within the realm of concrete frames.

1.6 Research Significance

Investigating the influence of diverse factors on the flexural stiffness of concrete elements holds profound significance in reassessing prevailing analyse methodologies. This study has the potential to uncover discrepancies or limitations within current methods, signalling the need for critical review and potential updates. Such findings could prompt the refinement and development of analysis techniques, aiming for heightened accuracy in predicting structural performance. Consequently, this advancement in analytical precision aligns with the pursuit of safer, economically feasible, and sustainable structural designs, fostering a paradigm shift toward enhanced structural integrity and resilience.

Chapter 2: Literature Review

2.1 Introduction

The objective of this literature review is to extensively delve into the realm of non-linear analysis concerning reinforced concrete frames, specifically focusing on the assessment of effective flexural stiffness under lateral loads. This comprehensive exploration aims to underscore the significance of employing a realistic value for effective stiffness in concrete elements, elucidating its direct correlation with the analysis accuracy and subsequent performance of reinforced concrete frames.

Moreover, the review endeavours to offer an encompassing overview of the myriad parameters influencing effective stiffness, scrutinizing their impact on structural behaviour. It seeks to present a detailed discourse on the intricate non-linear behaviour exhibited by concrete materials, accentuating the complexities arising from both material non-linearity and the geometric intricacies inherent in structural frameworks. This multifaceted analysis aims to offer a nuanced comprehension of the interplay between these factors and their collective influence on the overall behaviour of reinforced concrete frames subjected to lateral loads.

2.2 Effective Stiffness for Concrete Building

In structural design, the effective stiffness plays a critical role in accurately predicting the behaviour of structural elements and systems. It refers to the stiffness that appropriately represents the actual response of the structure under applied loads, taking into account various factors that influence its behaviour.

One of the key factors considered in determining the effective stiffness is material non-linearity. Many structural materials, such as concrete, steel, and composites, exhibit non-linear behaviour under certain loading conditions. Non-linear material models, such as plasticity models or stress-strain curves, are employed to capture the non-linear response

accurately. By incorporating these material non-linearities, the effective stiffness ensures that the structural analysis and design reflect the actual behaviour of the materials being used.

Geometric non-linearity is another significant factor considered in determining the effective stiffness. Geometric non-linearity accounts for large deformations and rotations in structural elements, particularly when dealing with significant displacements or large loads. The effective stiffness takes into account the changing lengths and rotations of the members, which can significantly affect the overall stiffness of the structure.

Time-dependent behaviour is also considered when determining the effective stiffness. Some structural materials exhibit time-dependent properties, such as creep and relaxation. The effective stiffness incorporates these time-dependent effects to accurately predict the long-term behaviour of the structure. Additionally, the effective stiffness considers the stiffness of connections between structural elements. Connections play a crucial role in transferring loads and can introduce additional flexibility or stiffness to the overall system. By accounting for connection stiffness, the effective stiffness accurately represents the behaviour of the entire structural system.

The boundary conditions of the structure also influence its overall stiffness. The effective stiffness takes into account the support conditions and restraints at the boundaries of the structure. These boundary conditions can significantly affect the structural response, and incorporating them into the effective stiffness ensures that the analysis accurately reflects the real-world conditions.

This research focus on the material and geometry non-linearity to be consider as factors that the effective stiffness provides a more realistic representation of the structural behaviour where it is used in structural analysis and design to determine deformations, stresses, and dynamic response under various loading conditions. Engineers rely on the

effective stiffness to ensure that the structure meets the required performance criteria, such as deflection limits, load-carrying capacity, and structural integrity.

2.3 Effective Stiffness Influence on Structural Analysis and Design

The significance of precise stiffness values for reinforced concrete elements becomes apparent in both structural analysis and design. This importance manifests in accurately estimating the lateral deflections of a structure and determining the impact of gravity loads, particularly in terms of p-delta values where lower effective stiffness leads to heightened p-delta effects within the structure. The distribution of the internal forces in structures also related to the stiffness of elements. Moreover, studies have shown that the improper adoption of elements stiffness result in inexact evaluation of the response of structures. For example, in the case of dynamic analysis this can lead to inaccuracy in the values of period of the structure, deformation demands, yield displacement, beside the distribution of loads.

2.3.1 *P-delta (P- Δ) Effect*

The significance of accurately determining column stiffness resonates profoundly in shaping the overall structural stability. This importance stems from the substantial influence of estimated P-delta effects on the structure. Lower stiffness attribution to columns amplifies the calculated P-delta effect on individual columns and extends its impact across entire story levels. Consequently, this amplification leads to a considerable increase in secondary moments, driving an inefficient and overly conservative structural design.

Conversely, assigning a higher value to effective stiffness inadvertently leads to an underestimation of secondary moment effects. This underestimation poses a direct risk to the stability of the building, emphasizing the criticality of striking an accurate balance in column stiffness considerations to ensure structural stability and integrity.

2.3.2 *The Distribution of the Internal Forces*

Mehanny, et al. (2001) claimed that In typical building designs with regular frames and structures, it's generally believed that the distribution of internal forces isn't affected much by the stiffness values used in analysis. However, there are cases where this assumption doesn't hold. For instance, in seismic rehabilitation following FEMA 273 guidelines, distinguishing between force and deformation design controlled structural components becomes crucial for accurately determining internal forces and deformations. Similarly, in lateral resisting systems with both frames and wall and also for the structures that used different construction materials for example steel and concrete, the assumed stiffness properties can significantly alter calculated internal force distributions. If these calculations deviate greatly from actual behaviour, it can result in larger-than-expected inelastic deformations and force redistribution.

Similarly, Khuntia & Ghosh (2004a) stated that, in the analysis of regular structures, there's a prevalent assumption that the distribution of internal forces remains largely unaffected by varying stiffness assumptions among structural members. However, this assumption holds validity only under the condition that the stiffness ratios between columns and beams at different joints remain relatively consistent as the structures subjected to increasing loads. Nevertheless, even in such cases, the P- Δ effects can amplify the internal forces at the ends of the columns.

Using incorrect moments of inertia for frame members can lead to non-conservative results. For instance, in a one-story one-bay frame under gravity loads, assuming a column moment of inertia (I) of $1.0I_g$ and a beam I of $0.3I_g$ (yielding a column-to-beam I/L ratio of 6.6, where L represents the column height-to-beam span ratio of 2), the maximum end moments in the columns can be over 30% larger compared to

assuming a column I of $0.5I_g$ and a beam I of $0.5I_g$ (which gives a column-to-beam I/L ratio of 2.0).

2.3.3 Influence of the Effective Stiffness on Dynamic Analysis

The impact on dynamic analysis can be elucidated by considering how the frequencies of structural vibrations are intricately tied to the square root of their stiffness. Alterations in stiffness coefficients have a profound effect on dynamic responses induced by seismic events, wind forces, or other applied loads. The chosen stiffness parameters wield significant influence over the computed response, the extent of which depends on specific circumstances and the degree of inelastic behaviour exhibited within the structure.

Kumar, & Singh (2010) agree of the effect of using realistic value, they stated “The use of realistic stiffness is also important because it directly affects the building periods and dynamic response, deflection and drift, and internal force distribution”

Due to the substantial influence wielded by the effective stiffness value, it becomes imperative to thoroughly investigate its implications on the design of buildings subjected to lateral loads. Understanding the extent of its impact involves an exploration of the methods endorsed within international codes, allowing a comprehensive assessment of their influence on structural design under lateral load conditions. This detailed examination is crucial for refining design practices and ensuring structural integrity in buildings exposed to such forces.

2.4 Existing Effective Stiffness Models (Simplified Methods for Estimating Effective Stiffness)

In general, design codes proposed the effective stiffness (EI_{eff}) as a percentage of the gross section stiffness (EI_g). ASCE 41-13 (The American Society of Civil Engineers) suggest these values to be from 0.3 for to 0.7 for columns, other values were suggested by FEMA-356 (The Federal Emergency Management Agency) which is 0.5 and 0.5 to 0.7 for beams and columns respectively. all these values were suggested based on the effect of the

axial load ratio. ACI-318-19 suggest 0.35 for beams and 0.7 for columns and walls in case of un-cracked section other wise 0.35 can be used.

Although the design codes are proposed the effective stiffness as a ratio of EI_g based on the effect of axial loads. Numerous studies have proven that multiple factors govern effective stiffness

Khuntia & Ghosh (2004a) based on analytical study determine the axial load, reinforcement ratio, eccentricity and compressive strength as a major factor influence the effective stiffness of concrete columns while all of the concrete cover, the reinforcement distribution and section shape can consider mislabel due to their minor effect. On the other hand, for beams the tensile reinforcement, the aspect ratio (b/h) and the compressive strength has considered a major factor influence the beams effective stiffness while it has found that the compression steel ratio has a navigable effect. Table (1.1)

The study covers all the practical range for columns where both normal and high strength concrete are adopted (4000 and 12000 psi), reinforcement ratios are 1% and 3% for axial load and eccentricity the covered rang is from 0.1 to 0.8. for beams similar concrete strength, tensile reinforcement ratio (0.5 to 2.5%) are used and b/h ratios (0.5 and 1). all parameter testes as the effective stiffness computing as a ratio of bending moment curvature ($EI_{eff} = M/\phi$) which computed up to the yield of tensile reinforcement and they explained that by (the value would drastically diminish after steel yielding. The stress-strain concrete model which used for the analysis of both normal and high strength concrete is

$$\frac{f_c}{f'_c} = 2 \frac{\epsilon_c}{\epsilon_0} - \left(\frac{\epsilon_c}{\epsilon_0}\right)^2 \dots (1)$$

Where f_c = compressive stress at a concrete strain of ϵ_c .

Assuming an ultimate failure strain (ϵ_u) equal to 0.003
 ϵ_0 , the strain corresponding to $f_c = f'_c$,
 $\epsilon_0 = 0.002$ for normal concrete (4000 psi)
 $\epsilon_0 = 0.0024$ for high strength concrete (12000 p

Khuntia & Ghosh (2004b) verify the previous mentioned proposed model based on experimental data, their examination involves a thorough comparison with various published test data, revealing a commendable alignment. The proposed stiffness formulations prove applicable across a wide range of applied loads, covering both service and ultimate loads. Both analytical and experimental results affirm that the flexural stiffness assumption from the ACI-318-02(0.35 and 0.7) code, utilized in the design of slender columns through the moment magnifier method is overly conservative. They suggest utilizing initial values of $0.35E_cI_g$ for beams and $0.7E_cI_g$ for columns in the preliminary analysis. Following the lateral load analysis, the effective stiffness should be computed using the equations proposed by Kuntia and Ghosh (2004) only if the calculated effective stiffness is found to be more than 15% conservative compared to the initial assumption, it is advisable to rerun the lateral load analysis with the revised value.

Additionally, after the analysis, inspect column ends for single-curvature bending in non-sway frames. If discovered, reduce the value of EI_e to 0.75 times its original magnitude and conduct a new analysis to ensure precise moment magnification in second-order elastic analysis and displacements in first-order elastic analysis, if necessary for stability index Q calculations.

The bending moments should be amplified by either δ_{ns} or δ_s , employing the relevant equations. The 0.75 factor in δ_{ns} (derived from Equation 2) is specifically relevant to non-sway frame columns experiencing single-curvature bending. This factor accounts for the gradual increase in initial eccentricity ($e = M_u/P_u$) observed in such cases, typically occurring when δ_{ns} surpasses 1.0, primarily observed in single-curvature columns.

For sway frames, the 0.75 factor should consistently be applied to P_{cs} , as δ_s invariably exceeds 1.0, leading to moment magnification.

$$\delta_{ns} = \frac{cm}{1 - p_u/0.75P_c} \dots\dots (2)$$

$$\delta_s = \frac{1}{1 - p_u/P_s} \dots\dots (3)$$

Elwood & Eberhard (2009) argue that the existing models of effective stiffness are conservative because they do not take into account the influence of the anchorage slip. It argued that the existing models commonly used for design applications tend to overestimate the estimated effective stiffness and are notably imprecise, as they often overlook the impact of anchorage slip on the column's effective stiffness.

They trend observed in various design guidelines and codes indicates that as the axial load increases, the normalized effective stiffness of the columns also increases. Additionally, the data reveals that the ratio of EI_{eff} (effective flexural rigidity) to EI_g (gross flexural rigidity) decreases as the span-to-depth ratio decreases, especially when the axial load is low. moreover the study conclude that each of the models has a common tendency to provide higher estimations of the effective stiffness when compared to the measured values, resulting in coefficients of variation that fall within the range of 35% to 58%.the study provide a new model that take into account flexure, bar slip and shear component of deformation and claimed that this model provide and accurate estimation of effective stiffness which introduce there factors in terms of axial load and span to depth ratio.

This model is proposed based on 366 columns (221 rectangular columns with rectangular transfer reinforcement and 108 columns with spiral transverse reinforcement) where tested in cantilever, double curvature and double-jointed configuration result in a

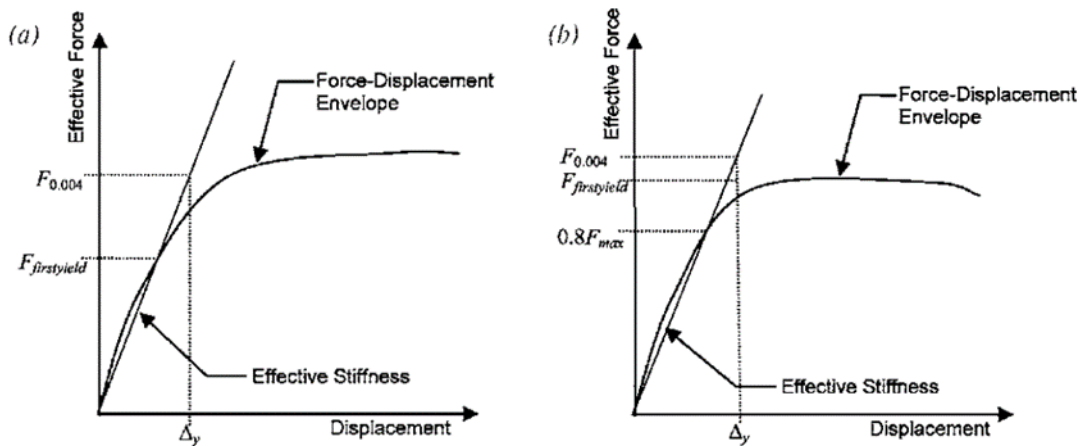
possibility of isolate column stiffness/flexibility. all columns where subjected to axial load that less than or equal $0.66 A_g f'_c$ and depth over ratio span that more than 1.4.

The effective stiffness calculated based on the load-displacement curve after corrected by the p-delta effect which is presented the stiffness at the first yield point weather it cross point the yield of tension reinforcement or the maximum concrete strain reached 0.002 which accord first.

Figure 2

Definition of Yield Displacement and Effective Stiffness from (Berry Et Al.2004) Test Data

For: (a) Yielding Columns; and (b) Columns that did not Yield



$$E_{\text{eff}} = \frac{F_{0.004} \Delta y^3}{3 \Delta y} \dots \dots (4)$$

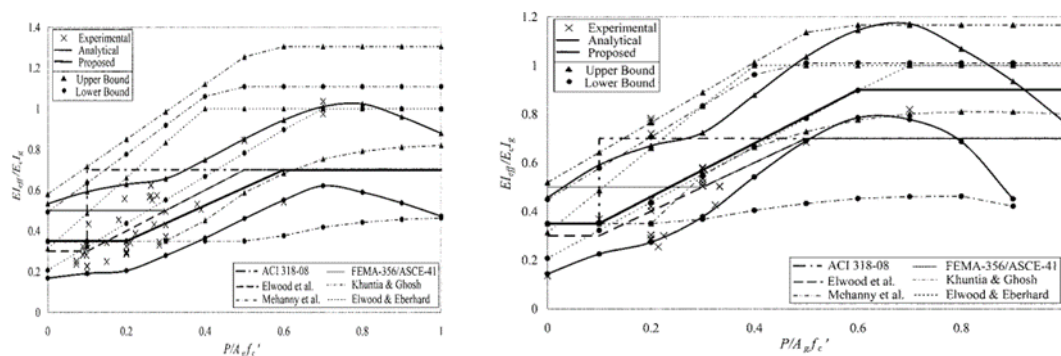
Kumar & Singh (2010) in their study examined the effect of reinforcement ratio, yield strength of steel diameter of longitudinal reinforcement, member length and depth and the concrete compressive strength for the reinforced concrete frames. the study had founded that the reinforcement ratio, compressive strength and member length are the major parameters which influence the flexural effective stiffness

They encompass a range of member lengths spanning from 0.16 meters to 4.67 meters, noting that columns typically stand between 3 to 4 meters in height. Furthermore, it asserts that the influence of member length becomes inconsequential for elements surpassing 4 meters. This is expounded upon by highlighting that as the member's length increases, its impact on effective stiffness decreases rapidly, ultimately indicating that beyond the 4-meter threshold, alterations in member lengths bear little significance on effective stiffness.

A comparison of different effective stiffness models with all possible axial load ratios from 0 to 1, the comparison includes the lower bound limits where the reinforcement ratio is 0.01, steel yield strength equal to 580 mpa, 32 mm diameter of longitudinal reinforcement, 3m length of member, cross section diameter $b=0.4$ and $0.8, 20$ and 60 for both normal and high compressive strength respectively. On the other hand, the upper bound limits is 0.4 reinforcement ratio, 380 mpa steel yield strength, 16 mm diameter, 4 m as member length, 0.4 m for width and length of the section, 40 and 80 mpa for normal and high compressive strength.

Figure 3

Comparison of Different Effective Stiffness Models with Analytical and Experimental Estimates for Normal and High Strength Concrete.



Note. (Kumar & Singh, 2010).

Bueno (2014) provides the effective stiffness as the percentage of the EI value, where the effective stiffness increases slightly with the increase of the floor numbers more details are presented in table (1.1)

Moreira & Martin (2018) provide an expression $EI_{eff} = \alpha * E_c I_c$ the values of α ranged from 0.17 to 0.14 for beams and from 0.66 to 0.72 for columns, for these values the effect of non-linearity of material and geometry is considered but the researcher was targeted the low-rise building (building that less than 4 stories).

The study based on analysis of 1, 2 and 3 floor buildings subjected to gravity and wind load, the analysis generated for first order taking into consideration the non-linear behaviour of the concrete material. The analysis was regenerated for second order analysis multiple times until the iteration analysis shows no difference in results. The building characterized by normal compressive strength for 3 and 4 m as floor to floor height taking into consideration different structural shapes and configurations for two cases of wind load 30 and 50 m/s. statistical analysis was used to proposed the final results that presented on table (1.1).

Recently, new models to predict the effective stiffness ratios of reinforced concrete recently proposed by researchers using GEP method (gene expression programming) based on the trained artificial neural network, models were developing using a database of existed samples of non-linear dynamic analysis in order to cover the non-linear behaviour in a superior way. more details presented by Das et, al. (2021)

Table 1*Existing Effective Stiffness Models Expressing the Affected Parameters*

Model	Column	Rectangular Beams
ACI-318a	0.35I _g cracked column 0.7I _g uncracked column	0.35I _g
FEMA 356	0.5-0.7I _g	0.5I _g
ASCE 41	0.7	0.3
New Zealand	(0.4-0.7)I _g	0.35 I _g
Paulay&priestley (1992)	0.8I _g (0.7-0.9)I _g , p>0.5f' _c A _g 0.6I _g (0.5-0.7)I _g , p= 0.5f' _c A _g 0.4I _g (0.3-0.5)I _g , p= - 0.05f' _c A _g	Recommended 0.4I _g from the range (0.3-0.5)I _g
Mehanny et al.(2001)	(0.4 + P/2.4P _b) < 0.9 EI _g P the applied axial compression P _b the axial compression at balance failure	
Khuntai&ghosh(2004), ACI-318b	0.35I _g ≤ (0.80 + 25ρ)(1 - $\frac{M_u}{P_u} -$ 0.5 $\frac{P_u}{P_o}$) ≤ 0.875 I _g Where: ρ longitudinal reinforcement ratio $\frac{M_u}{P_u}$ eccentricity $\frac{P_u}{P_o}$ axial load ratio	0.25 I _g ≤ (0.1 + 25 ρ) $\left(1.2 - 0.2 \frac{b_w}{d} \right)$ I _g ≤ 0.5I _g Where: ρ longitudinal reinforcement ratio b _w width of the beam d clear high of the section
Kenneth et, al.	$\frac{E_{eff} calc}{EI_g} = \frac{0.45 + 2.5P/Ag f'_c}{1 + 110(\frac{dp}{D})(\frac{D}{a})}$ $\leq 1 and \geq 2$ Where Dp/D approximate = 1/18 for building columns	

Kumar, & Singh(2010)	For normal concrete $0.35 \quad \text{for } P/Agf_c' \leq 0.2$ $0.175 + 0.875 \frac{P}{Ag f_c'}$ for $0.2 \leq \frac{P}{Ag f_c'} \leq 0.6$ $0.7 \quad \text{for } 0.6 \leq \frac{P}{Ag f_c'}$ For high- Strength concrete $0.35 \quad \text{for } P/Agf_c' \leq 0.1$ $0.24 + 1.1 \frac{P}{Ag f_c'} \quad \text{for } 0.2 \leq \frac{P}{Ag f_c'} \leq 0.6$ $0.9 \quad \text{for } 0.6 \leq \frac{P}{Ag f_c'}$	
Bueno(2014)	Building with one floor $\alpha_p = 0.6$ Building with two floor $\alpha_v = 0.6$ Building with three floor $\alpha_v = 0.7$ Building with 4 to 10 floor $\alpha_v = 0.8$	Building with one floor $\alpha_v = 0.2$ Building with two floor $\alpha_v = 0.3$ Building with three floor $\alpha_v = 0.3$ Building with 4 to 10 floor $\alpha_v = 0.4$
Moreira&Martin (2018)	Building with one floor $\alpha_p = 0.66$ Building with two floor $\alpha_v = 0.71$ Building with three floor $\alpha_v = 0.72$	Building with one floor $\alpha_v = 0.17$ Building with two floor $\alpha_v = 0.15$ Building with three floor $\alpha_v = 0.14$

2.5 Effective Stiffness Parameters

Existing models in the literature establish a consensus indicating that the effective stiffness of columns is notably influenced by the reinforcement ratio, compressive strength, and member length. These factors, alongside several others, must be duly considered, as their impact varies depending on the magnitude of the axial load. Understanding the

interplay among these factors is crucial in comprehending the nuanced effects on effective stiffness in columns.

2.5.1 *The Influence of the Reinforcement Ratio*

khuntia & ghosh(2004a) explore the high influence of the reinforcement ratio by detailing that the effective stiffness ratio is always high for higher area of reinforcement steel in all the practical cases of different values of axial load and eccentricities. Moreover, Kumar & Singh (2010) stated that “for beam members, and columns with a low axial load ratio, the reinforcement ratio the most governing parameter”.

Dehkori,et al. (2019) add that, the effective stiffness ratio, which relates to the ratio of flexural and effective stiffness to gross section stiffness, showed a strong dependency on the reinforcement ratio where A rise in the reinforcement ratio result in a rise in the effective stiffness for all axial load ratios, variation with axial load ratio was observed to increase mildly up to an axial load ratio of 0.2, followed by a rapid increase and reaching a peak in the range of 0.6 to 0.8, and then decreasing. A similar pattern was observed for flexural stiffness.

There is no dispute over this, as the tensile- resistance nature of steel reduces the occurrence of cracks within the concrete section which improve its flexural stiffness.

2.5.2 *The Influence of the Compressive Strength*

In the realm of reinforced concrete columns, the reinforcement ratio emerges as the principal parameter dictating effective stiffness under low axial load conditions. However, in instances of high axial load, the compressive strength surpasses the reinforcement ratio, assuming a pivotal role in determining effective stiffness within these columns. This shift in dominance between the reinforcement ratio and compressive strength signifies a critical transition influenced by varying axial load magnitudes within the structural context.

Employing high-strength concrete demonstrates a substantial enhancement in the effective stiffness of structural sections subjected to lateral loads. Notably, an analysis conducted on columns revealed a remarkable 32% increase in effective stiffness when utilizing a compressive strength of 12,000 psi, compared to 4,000 psi. This improvement was observed under specific conditions: an axial load ratio of 0.44 and an eccentricity value of 0.25. Moreover, the impact of high-strength concrete on beam sections proved significant, emphasizing that the rise in the Young's modulus of elasticity of concrete (E_c) cannot be disregarded due to its influence on structural behaviour.

Kumar & Singh (2010) Acknowledge that in their research on the Structural Performance Database, they conducted tests utilizing varying concrete compressive strengths—specifically, 20, 40, and 80 MPa. Throughout the study, parameters such as dimensions ($B = D = 0.4$ m), steel yield strength ($f_y = 480$ MPa), reinforcement ratio ($\rho = 0.02$), bar diameter ($d_b = 22$ mm), and length ($L = 3$ m) remained constant. The correlation between concrete compressive strength and effective stiffness proves intricate. Within the axial load ratio range of 0.4 to 0.7, a notable rise in the effective stiffness ratio occurs with heightened concrete compressive strength. Conversely, at low and high axial loads, the impact of concrete compressive strength is diminished and inverted, resulting in a reduction of the effective stiffness ratio ($EI_{eff}/E_c I_g$).

2.5.3 Member Length

The relationship between the length of concrete elements and their effective flexural stiffness is typically characterized by a proportional correlation. In general terms, longer concrete elements tend to exhibit lower effective flexural stiffness compared to shorter elements. This relationship arises due to the increased susceptibility of longer elements to undergo greater deflections and deformations under applied loads, thereby resulting in a reduction in their effective flexural stiffness. Conversely, shorter concrete

elements usually manifest higher effective flexural stiffness due to their reduced susceptibility to excessive deflections, thus displaying a more rigid response to applied loads.

2.5.4 Axial Load

The axial load ratio is considering the main factor that directly affect the estimation of the effective stiffness, this is observable from the method that used to estimate the flexural stiffness in the simplified methods that mentioned previously, where, it's the only factor that counted by Mehanny et al. (2001) model. Similarly, khuntia & ghosh, (2004a) consider the axial load ratio one of the influencing factors on the flexural stiffness. Also, the influence of other parameters is assessed by the ratio of the axial load as mention before both compressive strength and axial load effect depends on the axial load ratio.

2.6 Reinforced Concrete Non-Linearity

2.6.1 Material Non-Linearity

Concrete material non-linearity refers to the behaviour of concrete under loading conditions where its response is not purely elastic but involves plastic deformation. In other words, the stress-strain relationship of concrete exhibits non-linear behaviour beyond a certain point, typically after reaching its peak strength. In the early stages of loading, concrete behaves linearly, meaning that the strain is directly proportional to the applied stress according to Hooke's law. However, as the stress increases, the concrete starts to undergo micro-cracking and other irreversible deformations, leading to a non-linear stress-strain relationship. This non-linearity is characterized by strain softening, meaning that the stiffness of concrete decreases as the strain increases.

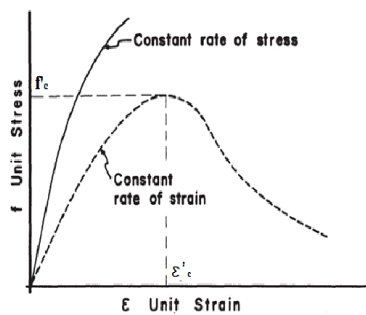
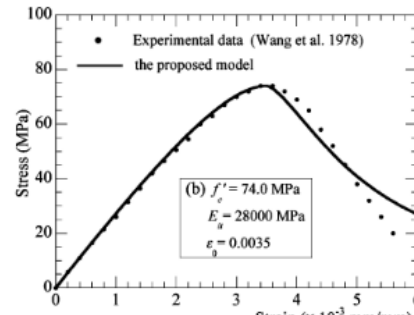
2.6.1.1 Stress-Strain Curve of Concrete Model Under Compression. Many studies were sleeked to capture the behaviour of concrete so many stress-strain models were provided in the literature. Generally, the existed stress-strain model for confined and

UN-confined normal and high strength concrete can be presented in three form, the first form based on Sargin et al. (1971) where the curve form follow the equation(10) many researchers adopt this study and develop it to be applicable for confined and nu-confined concrete and for wide range of compressive strength from(20 to 130 MPA).Second form is based on Kent and Park (1971) with second order parabola for ascending branch (independent of condiment) and strait line for the descending branch (depend on the condiment).Third form is established by Popvics (1973), the major difference of this model and the two mentioned model that it has one continues function for the both branches of the curve [10].Table (2.2) presented number of the existed models

$$Y = (AX + (D-1) X^2) / (1 + (A-2) X + DX^2) \dots \dots \dots (10)$$

Table 2

Existing Stress-Strain Behaviour of Concrete Under Compression

Author(year)	Model description	Valid Fc (mpa)	Curve shape
Popovics (1973)	$\frac{f_c}{f'_c} = \frac{\beta \left(\frac{\epsilon_c}{\epsilon'_c} \right)}{\beta - 1 + \left(\frac{\epsilon_c}{\epsilon'_c} \right)^\beta}$ $\beta = 0.058 f'_c + 1$	Up to 51	
Wang et al. (1978)	$\frac{f_c}{f'_c} = \frac{A \left(\frac{\epsilon_c}{\epsilon'_c} \right) + B \left(\frac{\epsilon_c}{\epsilon'_c} \right)^2}{1 + C \left(\frac{\epsilon_c}{\epsilon'_c} \right) + D \left(\frac{\epsilon_c}{\epsilon'_c} \right)^2}$ A,B,C and D are constant which can be estimated by considering the condition A. $\frac{f_c}{f'_c} = 0.45 \quad \text{for} \quad \frac{\epsilon_c}{\epsilon'_c} = \frac{0.45}{\frac{E_{lt}}{E_c}}$ $\frac{f_c}{f'_c} = 1 \quad \text{for} \quad \frac{\epsilon_c}{\epsilon'_c} = 1$	Up to 71	

Carreira & chu
(1985)

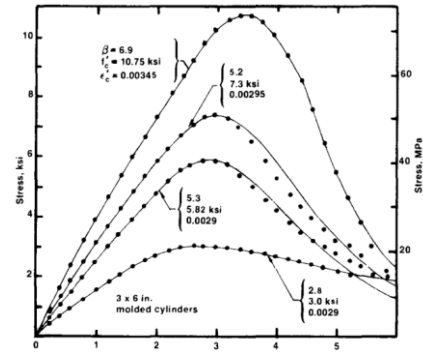
$$\frac{f_c}{f'_c} = \frac{\beta(\frac{\epsilon_c}{\epsilon'_c})}{\beta - 1 + (\frac{\epsilon_c}{\epsilon'_c})^\beta}$$

$$\beta = \frac{1}{1 - (\frac{f_c}{\epsilon_c E_{it}})}$$

$$E_{it} = \frac{f'_c}{\epsilon_c} \left(\frac{24.82}{f'_c} + 0.92 \right)$$

$$\epsilon'_c = (1680 + 7.1 f'_c) * 10^{-6}$$

23 to 80



Test data in Reference 10 and fitted stress-strain diagrams

Hsu & Hsu (1994)

for $0 \leq \epsilon \leq \epsilon_c.lim$

$$\frac{f_c}{f'_c} = \frac{n\beta(\frac{\epsilon_c}{\epsilon'_c})}{n\beta - 1 + (\frac{\epsilon_c}{\epsilon'_c})^{n\beta}}$$

for $\epsilon > \epsilon_c.lim$

$$\frac{f_c}{f'_c} = 0.3 f'_c e^{-0.8(\frac{\epsilon_c}{\epsilon'_c} - \frac{\epsilon_c.lim}{\epsilon_c})}$$

$$\beta = (\frac{f'_c}{65.23})^{3+2.59}$$

$$E_{it} = 0.0736 w^{1.51} f'_c^{0.3}$$

$$\epsilon_0 = (1680 + 7.1 f'_c) * 10^{-6}$$

for $0 \leq \epsilon \leq \epsilon'_c, n=1$

for $\epsilon'_c \leq \epsilon \leq \epsilon_d$

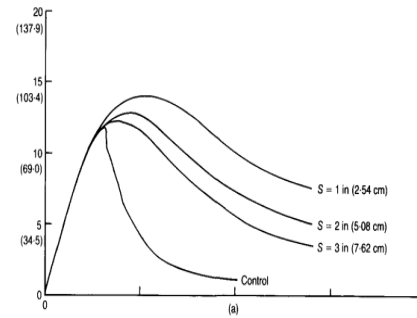
$n = 1$ if $f'_c < 62 \text{ mpa}$

$n = 2$ if $62 \text{ mpa} < f'_c < 76 \text{ mpa}$

$n = 3$ if $76 \text{ mpa} < f'_c < 90 \text{ mpa}$

$n = 5$ if $f'_c > 90 \text{ mpa}$

More
than 69



Stress-strain curves for HSC at various tie spacings; (b) generated analytical stress-strain curves at various volumetric ratios

Wee et al. (1996)

for $f'_c \leq 50 \text{ mpa}$

$$\frac{f_c}{f'_c} = \frac{\beta(\frac{\epsilon_c}{\epsilon'_c})}{\beta - 1 + (\frac{\epsilon_c}{\epsilon'_c})^\beta}$$

for $50 < f'_c \leq 120 \text{ mpa}$

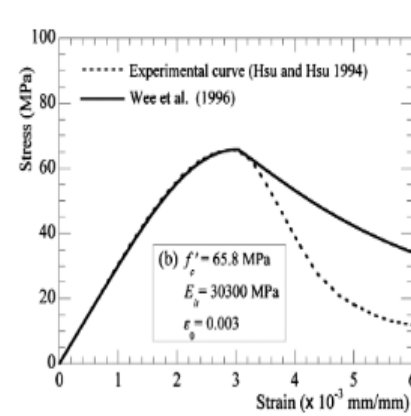
$$\frac{f_c}{f'_c} = \frac{k1\beta(\frac{\epsilon_c}{\epsilon'_c})}{k1\beta - 1 + (\frac{\epsilon_c}{\epsilon'_c})^{k2\beta}}$$

$$\beta = \frac{1}{1 - (\frac{f_c}{\epsilon_c E_{it}})}$$

$$E_{it} = 10,200 (f'_c)^{\frac{1}{3}}$$

$$k1 = (\frac{50}{f'_c})^3, k2 = (\frac{50}{f'_c})^{1.3}$$

50 to 120



Comparison of Proposed Model with Test-Data

Razvi & Saatciglu (2005)

Ascending branch

30 to 130

$$\frac{f_c}{f'_c}$$

$$= \frac{r \left(\frac{\varepsilon_c}{\varepsilon_{cc}} \right)}{r - 1 + \left(\frac{\varepsilon_c}{\varepsilon_{cc}} \right)^r}$$

Descending branch

$$\frac{f_c}{f'_c} = \frac{\varepsilon - \varepsilon_{cc}}{\varepsilon_{cc} - \varepsilon_{cc85}}$$

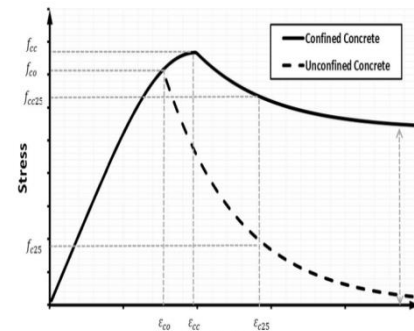
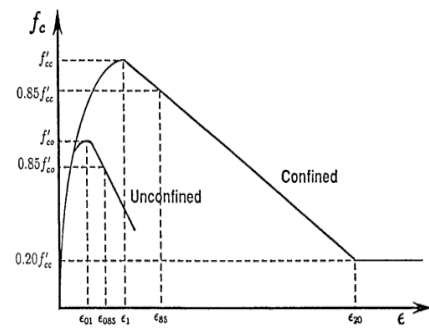
Baduge, et al (2018).

Ascending branch

100 to 150

$$\frac{f_c}{f'_c} = \frac{k \left(\frac{\varepsilon_c}{\varepsilon_{cc}} \right)}{k - 1 + \left(\frac{\varepsilon_c}{\varepsilon_{cc}} \right)^k}$$

$$k = \frac{Et}{Et - \left(\frac{f_{cc}}{f_{cc}/\varepsilon_{cc}} \right)}$$



It's worth noting that the shape of the stress-strain curve can be influenced by various factors, including the concrete mix design, curing conditions, aggregate properties, and the presence of reinforcing materials such as steel bars. Different types of concrete, such as normal concrete, high-strength concrete, or fibre-reinforced concrete. Confinement and confinement of concrete exhibit variations in their stress-strain behaviour but it's noted that the factored that affect the stress-strain curve under compression significantly are the compressive strength and the confinement where the high strength concrete exhibit differently.

Hsu & Hsu (1994) Proposed a model to demonstrate the behaviour of high-strength concrete based on an experimental investigation using various samples. These samples had a compressive strength exceeding 69 MPa and were created by combining water-free admixture, cement, sand, aggregate, silica fume, and super plasticizers. The study included three different spacing configurations to examine the confined effect.

The results indicated that the strain value corresponding to the peak stress in high-strength concrete is higher compared to lower strength counterparts. This behaviour could

not be adequately described by strains of 0.002 and 0.003. Furthermore, the ascending branch of the stress-strain curve for high-strength concrete appeared to be more linear and steeper, while the descending branch displayed a steeper slope. By analysing the crack pattern of the high-strength concrete, it was observed that the broken surface of the concrete cylinders appeared smoother. This surface also passed through the aggregates used in the concrete mixture.

Baduge, et al. (2018) focuses on stress-strain models for very-high strength concrete (VHSC) in both confined and unconfined conditions. Calming that, there are only a few theoretical models available in the literature to predict the stress-strain behaviour of confined VHSC which are not accurate valid for compressive strengths of 150 MPa or higher. This study presents experimental stress-strain data from twenty-two VHSC samples with compressive strengths ranging from 120 MPa to 160 MPa, which were confined by lateral reinforcement which used to develop a new stress-strain model specifically for confined VHSC. Additionally, it proposes a novel theoretical approach that considers shear decay at the failure plane, passive confinement of transverse reinforcement, and dowel action of reinforcement to predict the stress-strain behaviour of concrete. By incorporating these phenomena, an analytical model for predicting the stress-strain behaviour of VHSC was developed. Through a comparison of the experimental results with existing stress-strain models, it was concluded that the new theoretical approach satisfactorily predicts stress-strain behaviour up to 160 MPa and outperforms other models.

2.6.1.2 Stress-Strain Curve of Concrete Model Under Tension. In tension, concrete exhibits distinctive behaviours characterized by its susceptibility to cracking along planes of elevated tensile stress. The material's inherent weakness in tension stems from the interplay between aggregates and the cement matrix. When subjected to tensile forces, concrete typically forms cracks, ranging from hairline fissures to more substantial

fractures. Despite this vulnerability, a bridging effect occurs as microcracks develop, distributing the tensile load and providing some limited tensile strength. However, concrete has restricted deformation capacity in tension, and once cracks initiate, they tend to propagate rapidly, leading to potential structural failure. To enhance tensile strength, reinforcement materials like steel bars are commonly incorporated into concrete mixes. The inclusion of additives and fibres can also improve post-cracking behaviour, controlling crack widths and contributing to a degree of ductility in the material. Understanding these tension-related behaviours is crucial for effective structural design and construction practices, emphasizing the importance of appropriate detailing and reinforcement to mitigate the challenges posed by concrete's limited tensile strength.

The behaviour of reinforced concrete under tension relies on various factors. Firstly, the reinforcement plays a vital role in restraining crack propagation. Additionally, a network of internal and external cracks forms around and along the bars, contributing to the behaviour. The strength and extensibility of the concrete itself, along with the effects of shrinkage, also come into play. Studies also have shown that, when concrete specimens are allowed to dry before testing, their tensile strength is lower compared to saturated test specimens. Drying shrinkage creates opportunities for crack growth, prioritizing them over the tensile stresses caused by external loads.

Carreira & chu(1985) Conducted a test to propose a stress-strain for concrete in tension. The test results and their reproducibility are influenced by several factors. These include the size, shape, and reinforcement of the specimen, the gage length (the distance between two measuring points), the strain rate, and the strain and stress measurement devices. The gage length should be sufficiently long to incorporate the effects of multiple primary crack systems. It should also be far enough from the ends of the specimen to

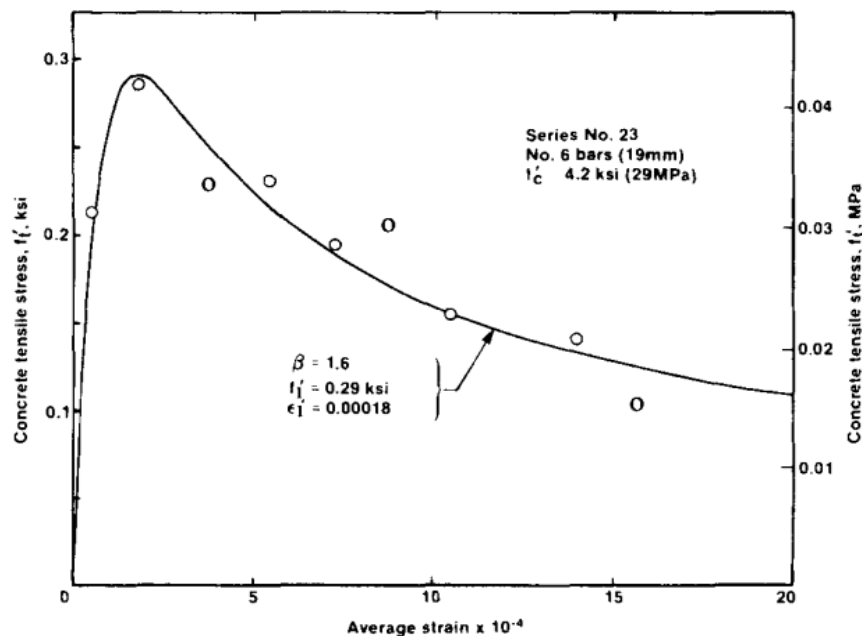
prevent reinforcement slippage. Ideally, the gage line should be at least one development length away from the specimen ends. The stress-strain relationships have been employed, including a descending branch. These relationships are derived from plain concrete testing data and the correlation between analytical solutions and experimental load-deflection data from reinforced concrete slabs. They discussing the use of the same formula that used to proposed the stress-strain curve of concrete under compression to proposed the concrete behaviour under tension

$$\frac{f_t}{f'_t} = \frac{\beta \left(\frac{\epsilon}{\epsilon'_t}\right)}{\beta - 1 + \left(\frac{\epsilon}{\epsilon'_t}\right)^\beta} \dots \dots (11)$$

The factored β for tension model is estimated to be different than compression where it's ranged from 1.45 to 1.95. Variations were noted across three different instances. Upon utilizing the methods delineated previous researches on this dataset, the predicted values for 13 spanned from 1.56 to 2.1. This particular observation suggests a consistency in the 13 values for initially uncracked concrete, indicating similarity between the tension and compression diagrams. . The values derived from literature for 13, when fitted with the data, consistently demonstrate a pattern of registering lower values compared to the predicted outcomes. For example, in Figure 3, the specifically noted value for 13 is 1.6, whereas the predicted range for 13 varies from 1.8 to 2.26. This observed difference between these values might be linked to a phenomenon of slippage that occurs at both extremities of the uncracked test specimen, resulting in a behaviour that mirrors that of concrete initially cracked.

Figure 4

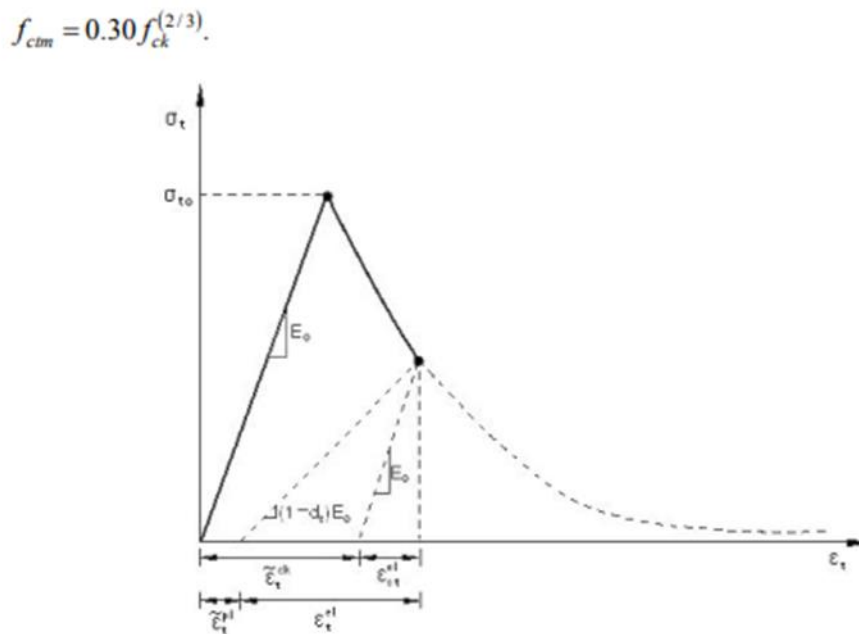
(Carreira & Chu, 1985) Stress-Strain Concrete Tension Model



Kmiecik & Kaminski (2011) The determination of the tensile strength of concrete under uni-axial stress is rarely conducted through a direct tension test due to the challenges associated with its execution and the substantial variability in the outcomes. Alternative approaches, such as sample splitting or beam bending, are often employed instead. Concrete undergoing tension is not considered a brittle-elastic material, and factors like aggregate interlocking within a crack and the adhesion of concrete to steel between cracks are considered. This assumption holds true when the crack pattern is indistinct or unclear. The strain following the occurrence of cracking is defined as the disparity between the overall strain and the elastic strain for the undamaged material.

Figure 5

Stress-Strain Tensile Model



The proper relation was proposed by, among others, Wang and Hsu

$$\sigma_t = E_c \epsilon_t \text{ if } \epsilon_t \leq \epsilon_{cr} \dots (12)$$

$$\sigma_t = f_{cm} \left(\frac{\epsilon_{cr}}{\epsilon_t} \right)^{0.4} \text{ if } \epsilon_t > \epsilon_{cr} \dots (13)$$

Where ϵ_{cr} stands for strain at concrete cracking.

2.6.2 Geometrical Non-Linearity

2.6.2.1 The P-Delta Effect Concept. The geometric non-linearity in reinforced concrete frames refers to the consideration of the effects of large deformations and displacements that occur in the structural elements when subjected to significant loads, seismic load for example. It accounts for the fact that the stiffness and behaviour of the frame change as the deformation increases. P-delta effect is one of the non-linearity sources, this effect considers the secondary moments induced by the axial loads in the columns. As the frame deforms under lateral loads, the vertical displacement of the

columns generates additional moments due to the eccentricity between the applied loads and the deformed shape of the structure. These secondary moments can significantly affect the overall behaviour and stability of the frame.

Large deflection: In the case of large deflections, the assumption of small deformations is no longer valid. The change in geometry leads to variations in the distribution of bending moments, shear forces, and axial forces along the elements of the frame. As a result, the stiffness of the members and the overall structural response undergo significant changes.

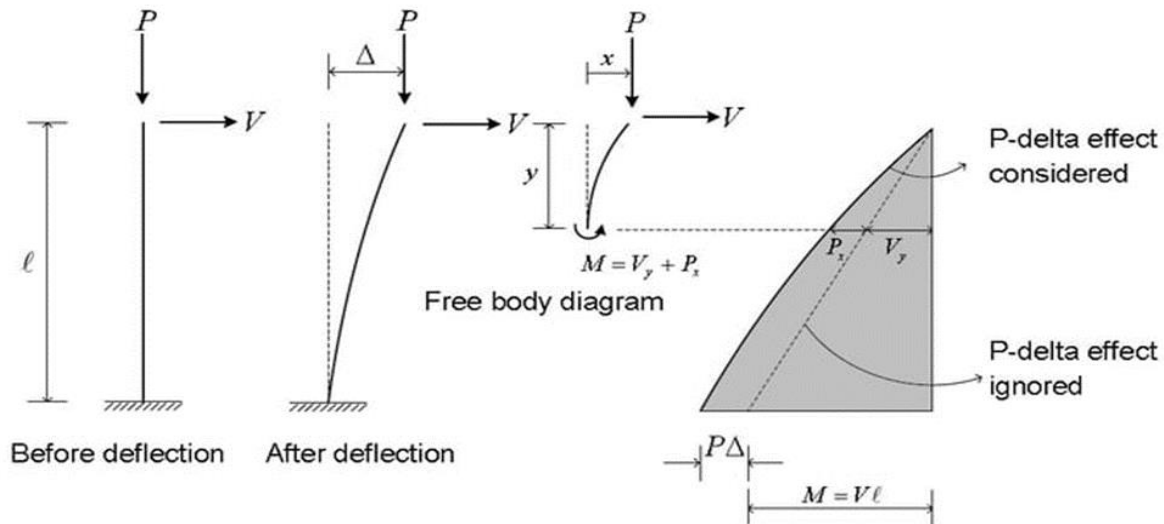
Member buckling: When subjected to compressive forces, columns and beams can undergo buckling, which a sudden lateral deflection or instability is caused by the load-induced bending moments. Buckling behaviour is highly non-linear and must be considered to accurately predict the response of reinforced concrete frames.

To calculate the stress of the vertical member especially the moment at the end of the section considering no deformations is exhibited for it the moment at the base is $M = VL$, as shown in Fig (6). The moment value diminishes linearly until zero at the loaded end. Where this is not the case with the existence of the deformations where an additional moment caused by axial load P acting with the lateral displacement Δ , in this case the moment does not vary linearly within the vertical element length. The additional moment now depends on the degree of the lateral displacement. $M = Vy + Px$. if the acting axial load of the member is too large, the lateral stiffness goes to zero, resulting in an infinity deflection at that point, which affect the stability of the structure while the vertical element will fall by buckling due to the p-delta effect.

There are two components that representing the P-Delta effect as shown in Fig (6), firstly the one refers to the effect of the local geometry change (The $P-\delta$), and secondly the effect due to relative displacement between member ends ($P-\Delta$).

Figure 6

Column P-Delta effect: Compressive and Lateral Forces Acting Simultaneously



The ACI-318-19 consider the concrete frame as sway frame if the Stability index from equation (5) does exceed 0.05 otherwise the frame will consider non-sway where the design pressure will be different when considering the moment magnification (considering the p-delta effect).

$$Q = \frac{\sum P_u \Delta^\circ}{V_{us} L_c} \dots\dots (5)$$

Where P_u and V_{us} are the total factored vertical load and horizontal story shear, respectively, in the story being evaluated,

Δ is the first order relative lateral deflection between the top and the bottom of that story due to V_{us} .

In the case of the sway frames secondary moment should calculate to consider the p-delta effect slenderness should consider where the column should consider slender if $k*Lu/r$ is more than 22

Moment magnification

$$M_2 = M_{2ns} + M_{2s} \dots\dots (6)$$

Where (δ s) Moment magnification can be calculated as one of three options:

$$(a) 1 / (1 - Q) \dots (7a)$$

$$(b) \frac{1}{1 - \frac{\sum p_u}{0.75 \sum p_c}} \dots (7b)$$

$$(c) \text{second order analysis}$$

In case of choosing (b)

$\sum p_u$ is the summation of factored gravity load of the story and $\sum p_c$ is the summation of critical buckling load for all sway-resisting columns in the story

$$P_c = \frac{\pi^2 (EI)_{eff}}{(kLu)^2} \dots (8)$$

Where EI eff in this case should be one of the following options

$$(9a) \dots \frac{0.4EI_g}{1 + \beta}$$

$$(9b) \dots \frac{0.2EI_g + EsI_{se}}{1 + \beta}$$

$$(9c) \dots \frac{EI}{1 + \beta}$$

2.6.2.2 The Consideration of P-Delta Effects in Structure Modelling. To analyse the geometric non-linearity in reinforced concrete frames, advanced numerical methods such as finite element analysis (FEA) are commonly employed. These methods take into

account the non-linear behaviour of the materials, large displacements, and the interaction between the structural elements.

Considering geometric non-linearity is crucial for the accurate prediction of the response and performance of reinforced concrete frames, especially under significant loading conditions, where the linear analysis assumptions may not be valid.

In the process of designing the program (ETABS), it is essential that the analysis results encompass P-delta effects. The treatment of P-delta effects varies depending on whether the components are classified as "braced" or "non-sway" or "unbraced" or "sway" in columns or frames. For braced column moments, the impact of P-delta is confined to "individual member stability." In the case of unbraced components, consideration should be given to "lateral drift effects" in addition to the individual member stability effect. The program assumes that braced moments originate from "dead" or "live" loads, while unbraced moments arise from all other types of loads. Concerning individual member stability effects, moments undergo magnification using factors.

Regarding lateral drift effects, the program assumes that P-delta analysis has been conducted, and the amplification is already integrated into the results. Moments and forces obtained from P-delta analysis are further amplified for the individual column stability effect if mandated by the governing code, such as the ACI 318-14 code. Users should be aware that the default analysis option for P-delta effect is deactivated. The user has the option to activate P-delta analysis and set the maximum number of iterations, with the default number being.

2.7 Static Linear Analysis

2.7.1 *What is Linear Static Analysing?*

The linear analysis of reinforced concrete structure is computational technique employed to scrutinize how reinforced concrete elements and systems respond to applied

loads. This method assumes that the construction materials of the concrete and the steel reinforcement remained linear elastic traits throughout loading. This method simplifies how reinforced concrete behaves by assuming that the stress-strain relationship for both concrete and steel is linear. It mainly focuses on minor displacements and rotations while ignoring substantial deformations and the effects of geometric non-linearity. Additionally, it assumes a linear distribution of loads across structural elements without considering how non-linear behaviour might redistribute the load. Despite these simplifications, the linear analysis provides an effective way to evaluate reinforced concrete structures, especially when the loads are within the elastic range and deformations are relatively small. Engineers can use this method to assess crucial aspects like member forces, deflections, and the overall structural response.

2.7.2 *Limitation of Static Linear Analysis*

The Linear elastic analysis is a useful analysis method in many scenarios in structures engineering, especially when the structure dealing with limited type of loading for example analysis structures under gravity load. But it has its limitations. One significant constraint is its inability to accurately represent the behaviour of structures when they experience large deformations or non-linear material responses. In fact, the construction materials including concrete and steel, exhibit non-linear behaviour under high loads or when reaching their ultimate capacity where this is expected in designing for lateral analysis especially when building subjected to earthquake.

Assuming the construction materials behave within the linear range of the stress strain curve, result in neglecting the after-yield behaviour of reinforced steel yielding or concrete cracking (all the non-linear behaviour). Additionally, this method often overlooks the redistribution of loads that can occur in structures with non-linear behaviour, potentially leading to inaccurate predictions of the structural response and capacity.

Therefore, while effective within the elastic range, linear elastic analysis might not accurately depict the actual behaviour of structures under extreme loading conditions or when non-linear material responses become significant.

All these limitations are the reason behind using the nonlinear methods for investigation the real performance of structures that can be subjected to extreme load.

2.8 Non-Linear Static Procedure (Pushover Analysis)

The push over analysis is non-linear analysis to assess the structural capacity under static horizontal loads growing until the collapse of the structure. The results of the pushover analyses are some capacity curves identified by the variation of the base shear in function of the displacement of a control point on the structure. In another words, the model incorporates the nonlinear stiffness and strength of the elements using a cyclic envelope curve, which inherently accommodates degradation from cyclic loading anticipated during earthquakes. Loads are imposed at nodes where dynamic inertia forces are likely to arise, and they are steadily augmented without any reversal of loads. A control point is defined for the target displacement, usually at the top (roof level) of the structure. The graph depicting the base shear force in relation to the displacement of the control point (typically the roof) is commonly referred to as the "pushover curve" of the building.

Using the pushover analysis overcome the limitation of the linear analysis of reinforced concrete frames which affect the accuracy of predictions. It assumes linear stress-strain relationships, neglecting material non-linearity, such as concrete cracking and steel yielding. Large displacements and rotations are ignored, disregarding geometric non-linearity. Contact and friction effects, as well as the $P-\Delta$ effect, are typically neglected. Time-dependent effects, load redistribution, and the non-linear behaviour of materials are not considered. To overcome these limitations, non-linear analysis techniques like the finite element method are used. Non-linear analysis captures material non-linearity,

geometric changes, and other factors, providing more accurate predictions of member forces and structural response. It allows for a better understanding of the behaviour of reinforced concrete frames under various loading conditions.

2.8.1 *The Advantages of the Pushover Analysis*

Static pushover analysis is a widely used approach for estimating the seismic forces and deformation requirements in order to assess the performance of both existing and newly constructed buildings due to its advantages that it is anticipated to furnish information that is beyond the reach of a linear elastic static or dynamic analysis

Krawinkler,1996 mentioned this advantages as follow:

- The force requirements for elements that may be prone to brittleness, such as axial forces in columns, connections for bracing, moments needed for beam-to-column connections, as well as shear force requirements in sturdy reinforced concrete spandrels beams and unreinforced masonry wall piers, etc.
- Predictions of deformation requirements for components that must undergo inelastic deformations to absorb the energy transmitted to the structure due to ground movements.
- The impact of the of strength deterioration of each structural elements on the performance of the overall structural system
- Locating critical regions where deformation demands are likely to be substantial, which should be the primary focus for meticulous detailing.
- Spotting points of strength discontinuities in either the plan or elevation that will result in characteristics in dynamic properties within the inelastic range.
- Prediction of interstory drifts, taking into consideration variations in strength or stiffness, and can be employed to manage structural damage and assess the influence of p-delta effects.

- Predictions of overall drift, which can be utilized to evaluate the risk of structural elements colliding with each other.
- Confirming the thoroughness and sufficiency of the load path involves assessing every aspect of the structural system, including its elements, connections, strong non-structural components, and the foundation system to ensure completeness and adequacy.
- Checking the thoroughness and sufficiency of the load-path, taking into account every element of the structural framework, all connections, sturdy non-structural elements with notable strength, and the foundation system.

2.8.2 The Disadvantages of Push Over Analysis

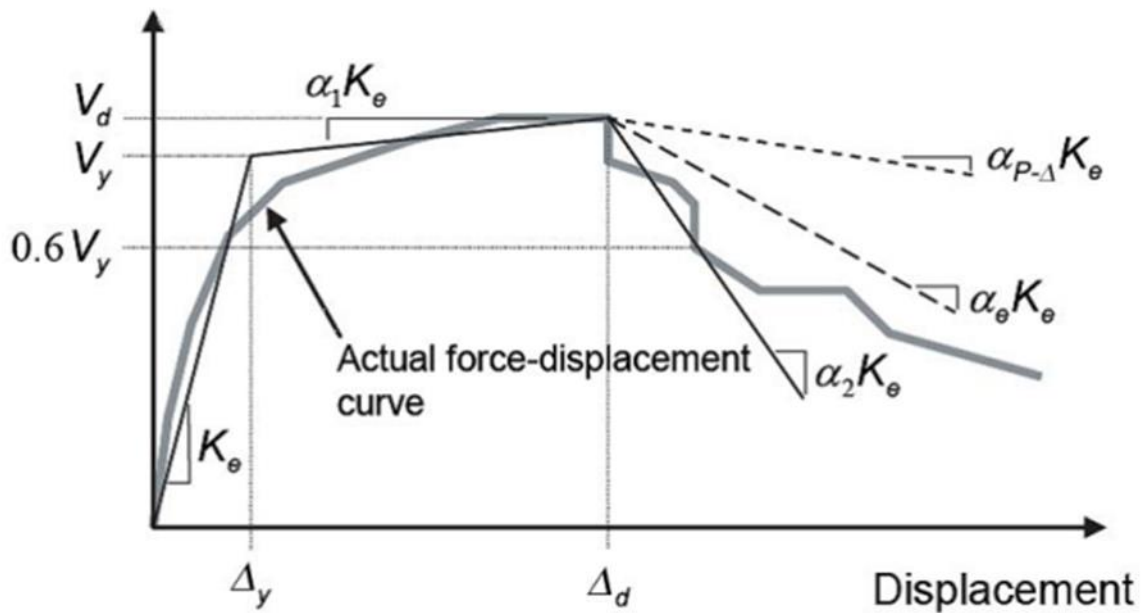
While the benefits of the NST analysis extend beyond even the capabilities of a linear elastic static or dynamic analysis, it's important to note that this method is best suited for low-rise, regular structures, where the primary mode of vibration is the fundamental sway mode. In the case of taller, slender, or irregular buildings, where multiple vibration modes come into play, the applicability of the NST analysis becomes less effective.

2.8.3 Pushover and Structural Stiffness

As illustrate in Fig (2.6) the pushover curve can be further simplified by idealized sloping branches of elastic, post-yield hardening and softening (degrading) behaviour, which is able to examine overall performance of the building. FEMA 440 and 440A outline the utilization of an idealized pushover curve in simplified non-linear dynamic analyses. They establish the minimum strength requirements for lateral dynamic instability. Additionally, FEMA 440A offers instructions for conducting these analyses on a structure-specific level, aiming to decrease uncertainties in the calculated target displacement compared to ASCE 41's default method.

Figure 7

Idealized Static Pushover Backbone Curve (Fema 2005)



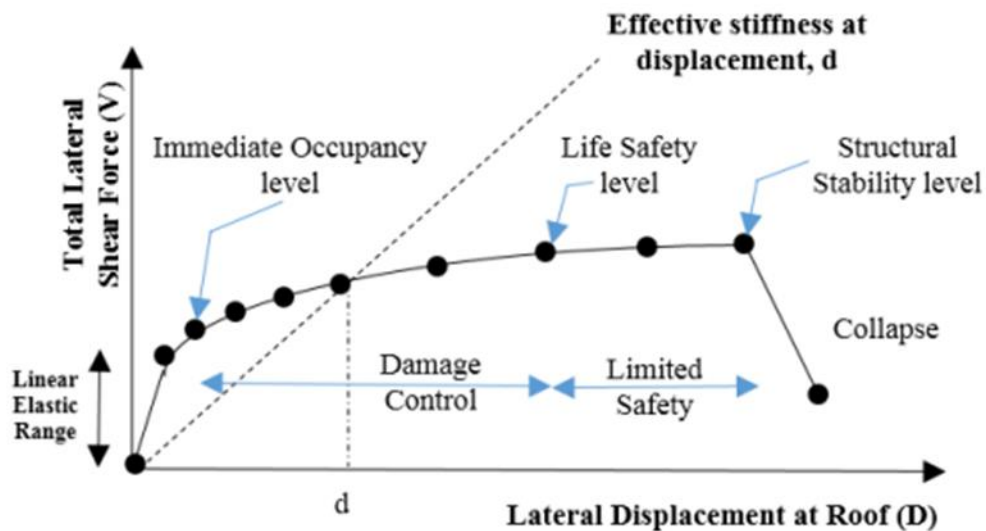
The initial line segment of the simplified force-displacement graph should initiate at the starting point and exhibit a gradient equivalent to the effective lateral stiffness, K_e . The effective lateral stiffness, K_e , shall be considered as the secant stiffness determined when the base shear force reaches 60% of the effective yield strength of the structure. The effective yield strength, V_y , should not exceed the highest base shear force at any point along the force-displacement curve. The second linear segment should symbolize the upward slope after yielding has occurred ($\alpha_1 K_e$), determined by a point (V_d, Δ_d) . A point should be located at the juncture with the initial line segment in a way that the areas both above and below the actual curve are roughly equal. (V_d, Δ_d) shall be a point on the actual pushover curve at the determined target displacement, or at the displacement that corresponds to the maximum base shear, whichever is least. The third linear segment should denote the negative slope after yielding ($\alpha_2 K_e$), and it is determined by the point located at

the conclusion of the positive post-yield slope (V_d , Δ_d) and the point where the base shear decreases to 60% of the effective yield strength.

It's commonly understood that flexural members typically demonstrate a noticeable decrease in stiffness at both the cracking and yield moments. If we're considering the design strength as the limit state, roughly corresponding to when significant nonlinearity occurs due to excessive steel yielding or concrete crushing, the load-deformation behaviour can be approximated as linear by using a secant stiffness to match deformations near the yield load. The effective flexural stiffness EI_{eff} at this stage can be reverse-calculated from displacements (D) obtained from tests or detailed analyses. Comparing this to the moment-curvature, the resulting effective stiffness EI_{eff} falls between that of the idealized cracked and uncracked sections.

2.8.4 Structural Performance Level

The performance point is the intersection of the capacity curve and the spectrum response curve in the capacity spectrum method. Fig (8) illustrates this point and provides information about the building's period and effective stiffness after plastic joint deformation. This data helps identify structural responses like deviation degree and plastic joint positions. Immediate Occupancy (IO) denotes a condition where a structure remains undamaged and fully functional after an earthquake. Life Safety (LS) means the structure withstands the earthquake with minimal damage, ensuring occupants' safety. Collapse Prevention (CP) refers to structures with significant damage but still standing. Structural Stability (SS) signifies partial or total damage, resulting in reduced strength and stiffness in the lateral force system.

Figure 8*Performance Levels of Structure*

Note. (Pierre& Hidayat, 2020)

The ACSE-41 explain the performance levels of each stage for the seismic force resisting concrete frames system that of the immediate occupancy, life safety and collapse prevention levels as follow:

Within the collapse prevention level, in primary structural elements, ductile components experience widespread cracking and the formation of hinges. Non-ductile columns might exhibit restricted cracking or splice failure. Secondary elements, such as columns and beams, suffer from substantial spalling, limited column shortening, severe joint damage, and instances of reinforcing bars buckling. Short columns experience severe damage due to drift, leading to transient drift causing extensive non-structural damage and significant permanent drift.

The frame will exhibit less damage for with in the safety performance level, thus the main element will display significant beam damage, cover spalling, and shear cracking in ductile columns, along with minor spalling in non-ductile columns. Additionally, for the

secondary element joint cracks will be evident. Ductile elements will exhibit major cracking and hinge formation, while some non-ductile columns may experience limited cracking or splice failure. Short columns will suffer severe damage, the anticipated transient drift causing non-structural damage and noticeable permanent drift.

The least damage off all is the immediate Occupancy level, where, in the primary elements Small cracks may occur, with the potential for limited yielding in a few specific areas. There might also be minor spalling of the concrete cover. Secondary element minor spalling seen in isolated spots within ductile columns and beams. Beams and columns exhibit flexural cracking, while joints display shear cracking. Temporary transient leading to minimal or no harm to non-structural components. There's virtually no lasting or significant permanent drift.

It's clear that the structure stiffness is proportional the performance level as the distortions changes significantly from performance level to another.

Chapter 3: Methodology

3.1 Introduction

The research aims are to study the influence of different parameters on the effective stiffness of the structure beside compare the differences between using non-linear analysis and simplified method that proposed by ACI -318 -19 code, in order to evaluate the effect of each parameter and the using of two methods on the structure performance. This chapter aims to elucidate the methodological approach and strategies employed to accomplish these objectives, thereby offering a comprehensive understanding of how these goals were effectively achieved. Within this chapter, a detailed exposition will encompass the research approach, design, strategy and analysis utilized in this study, providing insight into the methodologies applied. Additionally, this section will delineate the limitations inherent in the study, offering transparency regarding its constraints and boundaries.

3.2 Research Philosophy

This research will adopt the Positivism emphasises where scientific methods for modelling and analysis will be used to achieve the study goal depend on the well-known structural engineering concepts based on the previous study through empirical observation and measurement, where Positivists aim for objectivity, reliability, and replicability in their research.

3.3 Research Approach

As the research problem explained in the first chapter the research aims to evaluate the simplified method of estimating the effective flexural stiffness to test if it conservative or not and to explore its influence of the structure performance, the method which adopted is analytical, deductive, quantitative method. Quantitative research is recognized as a structured investigation into phenomena by gathering numerical data and applying statistical, mathematical, or computational methods. Rooted in the positivist paradigm,

quantitative research embraces approaches centered on statistical analysis, incorporating techniques such as inferential statistics, hypothesis testing, mathematical presentations, experimental and quasi-experimental designs, randomization, blinding, structured protocols, and questionnaires featuring a limited range of predetermined responses.

Quantitative, method will be appropriate to check each parameter effect and to compare the result of the two methods. Quantitative methods serve as a suitable avenue for assessing the impact of parameters on structural stiffness. These methods involve numerical measurements and statistical analyses that provide precise and measurable data. Through quantitative analysis, researchers can systematically quantify and analyse the influence of parameters on structural stiffness with a focus on numerical trends, correlations, and statistical significance. Techniques such as experimental testing, numerical simulations, and statistical modelling enable precise measurements and comparisons, allowing for a quantitative evaluation of how variations in parameters directly affect structural stiffness. The use of quantitative approaches offers a structured and objective means to quantitatively measure and comprehend the specific effects of parameters on structural stiffness.

3.4 Research Design

66 one bay- one story (frame structure presented in fig10) concrete frame with different parameters (compressive strength, column reinforcement ratios, column length and axial load) are modelled and analysed using finite element software (ETABS), the analysis were conducted twice using the non-linear static analysis for each frame. Firstly, columns and beams flexural stiffness are assigned as $0.7EI$ and $0.35EI$ respectively, pushover analysis was generated and the displacement corresponding to the yield base shear is recorded. Then the analysis was repeated considering the full flexural stiffness for elements to capture the inelastic displacement from the pushover (ductility curve). see fig

(11) The result was subjected to statistical analysis to compare the results for the two cases and to check the parameter effects on the overall frame performance of the structure.

Figure 9

Research Concrete Frame Model

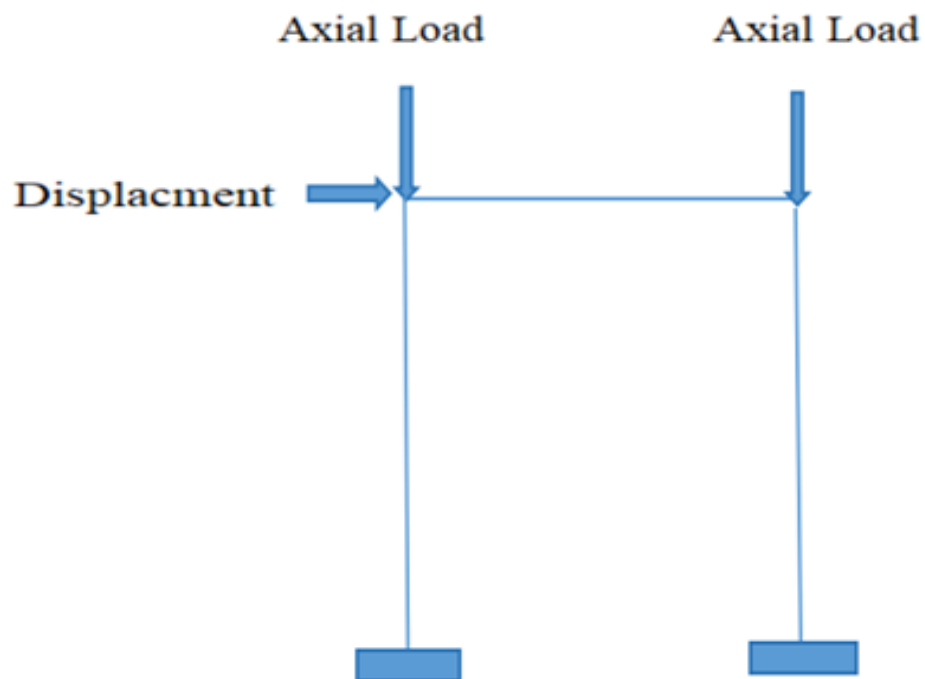
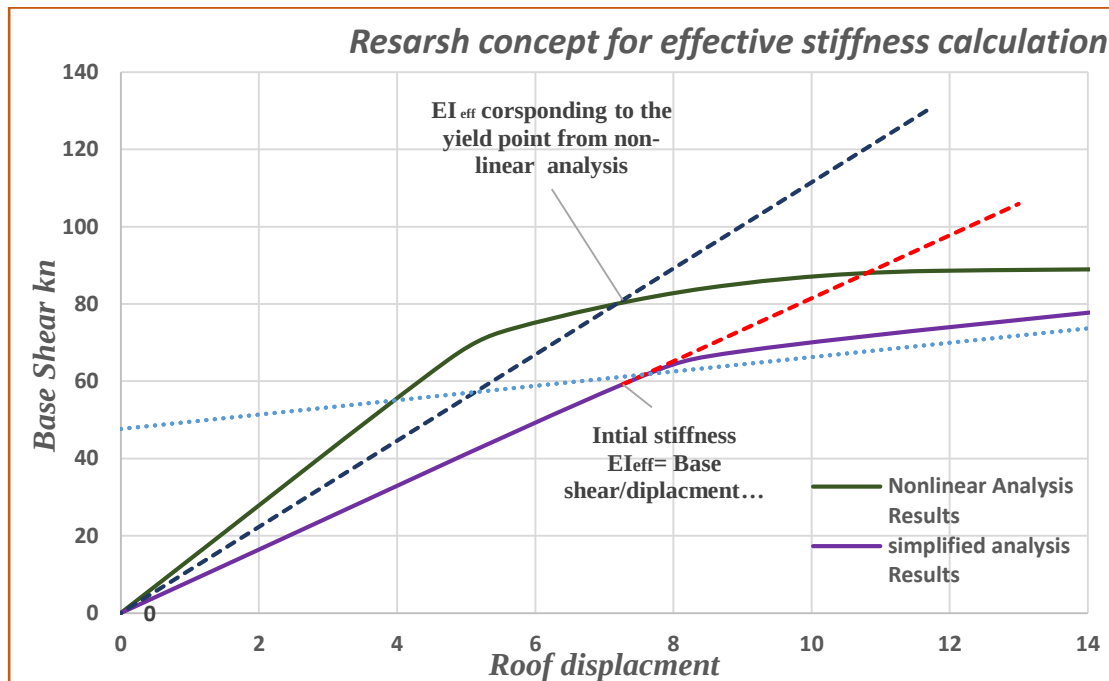


Figure 10*Effective Stiffness Calculation Method*

All the frames were modelled and analysed using ETABS v21.1.0 software.

ETABS v21.1.0 Tabs software is a widely used engineering which indicates its effectiveness in analysing and designing the concrete structures. ETABS allows for the consideration of material non-linearity, enabling the modelling of non-linear behaviour it's also account for geometric non-linearity. Since it includes P-Delta analysis capabilities, accounting for the second-order effects that arise due to the interaction between axial loads and lateral displacements. ETABS provides tools for pushover analysis, allowing engineers to evaluate the capacity of structures to resist lateral forces.as well it has been used in large number of academic researches (mentioning in references).

In another words, the software application ETABS, specializing in finite element analysis, is employed for the generation of a comprehensive 3D model and the subsequent execution of various analyses. This sophisticated software exhibits the capability to

forecast the geometric non-linear tendencies inherent in space frames when subjected to either static or dynamic loads. Noteworthy is its adeptness in considering the intertwined influences of both geometric non-linearity and material in-elasticity during the analytical processes, thereby contributing to a more accurate representation of structural behaviour under diverse loading conditions. In addition to how simple it is to use.

The static non-linear analysis technique is adopted. as explained previously this method superior to both linear and dynamic analysis on many points, the most important point that it will result in a load - displacement curve that allow to check the global lateral stiffness at each load level for each frame

3.5 Modelling and Analysis

The parameters that chosen for the analysis are:

1. The frame height (columns length) were considered for 4m and 5m.
2. The compressive strength of the frame were adopted for 3 cases 40mpa , 80 map and 120 mpa
3. The column reinforcement ratio are decided to use are 1% 2% and 3.3%.
4. The axial load is considered as 500kn, 350, 200, and 100 kn for frames with high compressive strength. Frame with a normal compressive strength (40 mpa) are analysed for 350,200 and 100kn on each column. The choosing for axial load on columns is limited to the code requirement ACI 318-19 section 6. 6.4.5.1, representing by the limitation of the p-delta effect for linear analysis.

All the chosen parameter is mentioned in the literature review it was agreed that it had a significant effect on the effective stiffness of the elements and it was chosen in this research to study their effect on the performance of the concrete Frame under lateral load.

Modelling details

Section definition:

For frame section the strong column weak beam is adopted to and the column section is constant for all case

(25cm*60cm)

Reinforcing details (6T16, 8T22 and 8T28) to represent different 3 ratios (1%, 2% and 3.3%)

Beam section is (20cm*50cm) with 4T18 with tension reinforcement ratio of 0.5%.

Material definition:

An extensive research are done to use an appropriate stress-strain model to simulate the concrete behaviour under lateral load, a comparison between existing model is done and illustrated at the appendices where a recommendation to study their effect will be presented in chapter 5 following the recommendation of (18) wang and his model will for high strength concrete and Carreira and chu (1985) will adopted for normal strength concrete.

The Plastic hinged definition meeting the requirements of the ASCE 41-17 code using table 10-7 for concrete beams and Table 10-8 and 10-9 for concrete columns.

The simplified analysis (linear elastic analysis) has been replaced by pushover analysis but only the first part of the curve (linear part) is adopted. The moment of inertia for column is assigned to be $0.7EI_g$ and the beam assigned as $0.35EI_g$ following the recommendation of the ACI-318-19. The global stiffness of the frame calculated at the first record point from the base shear-deflection curve in order to measure the initial stiffness where no cracks forms yet (this mean: the measured stiffness of the frame express the stiffness equivalent to seventy percent of the total stiffness of the column and thirty-five percent of the total stiffness of the beam) all data recorded for each frame to present the analysis result by simplified method. Again, the analysis is repeated but this time assuming the full inertia of

the frame element and the global stiffness is calculated at the equivalent displacement to the yield point. The geometric nonlinearity (p-delta) takes into consideration for two cases regardless the permission of the ACI 318 to ignore it if stability index is less than 0.5. (As detailed in chapter 2)

The results of the 66 frames are subjected to statistical analysis. All the results are illustrated and discussed in chapter 4 (results and discussions)

3.6 Limitation of Study

The study represents the global stiffness of the frame near at incipient yield the linear pre-yield and post yield region, and its applicable to assess the performance of the structure that subjected to lateral wind load. For frame under seismic its applicable to evaluate frames that designed based on immediate occupancy performance level.

In addition, this study covering the simplified effective stiffness that proposed by the ACI-318-19 assuming $EI_{eff} = 0.7 E_c I_g$ for columns and $EI_{eff} = 0.35 E_c I_g$ for beams. And the results are not covering the all-simplified methods

Chapter 4: Results and Discussion

4.1 The Influence of the Study Parameters on the Structural Performance

While there are not any significant differences observed between utilizing simplified or non-linear analysis methods, the findings reveal that the analysis results exhibit a high coefficient of variation, specifically at 41.8 percent, see table (4) this can be elucidated by considering the influence of various parameters utilized during the analysis. The correlation for each parameter are found as following:

4.1.1 Reinforcement Ratio

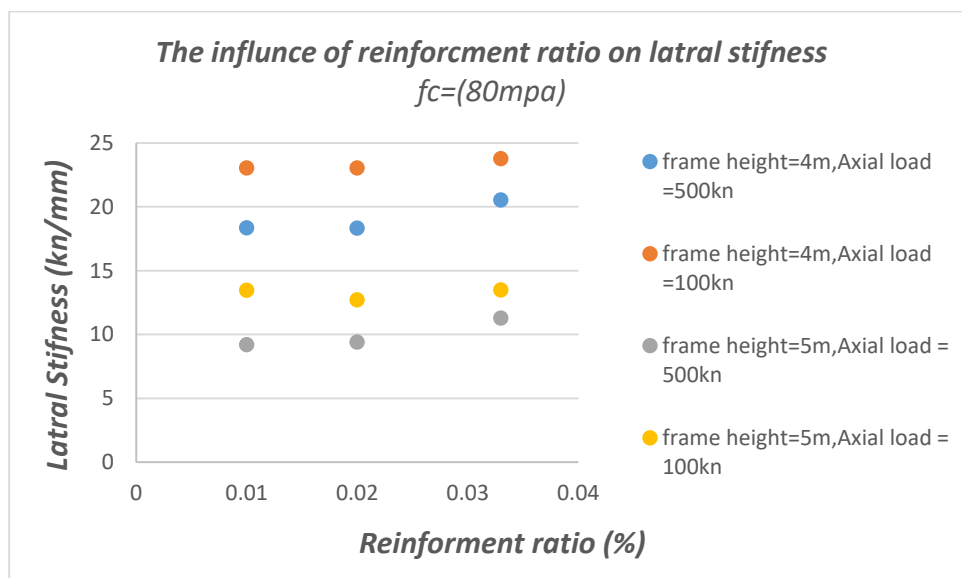
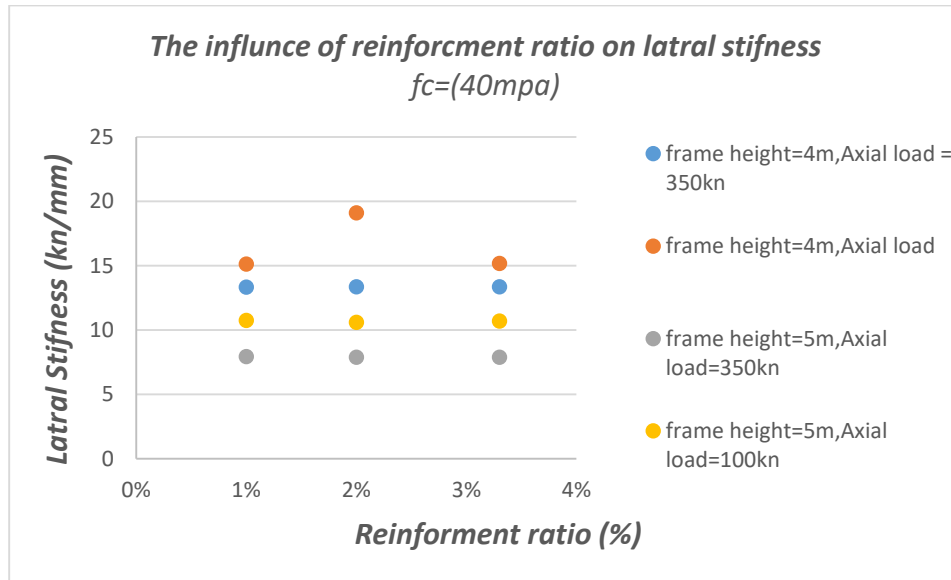
Although all the studies have shown the significance effect of the reinforcement ratio for the flexural effective stiffness of the columns, the analysis results show no effect for the reinforcement ratio showing low correlation coefficient that less than 0.2 for all the cases. This result does not negate the influence of these factors on the flexural stiffness, but it proves that this parameter has no significant effect on the overall performance of the frame of the frame under lateral which weakens the hypothesis that taking approximate value of flexural stiffness can affect the performance of the whole structure.

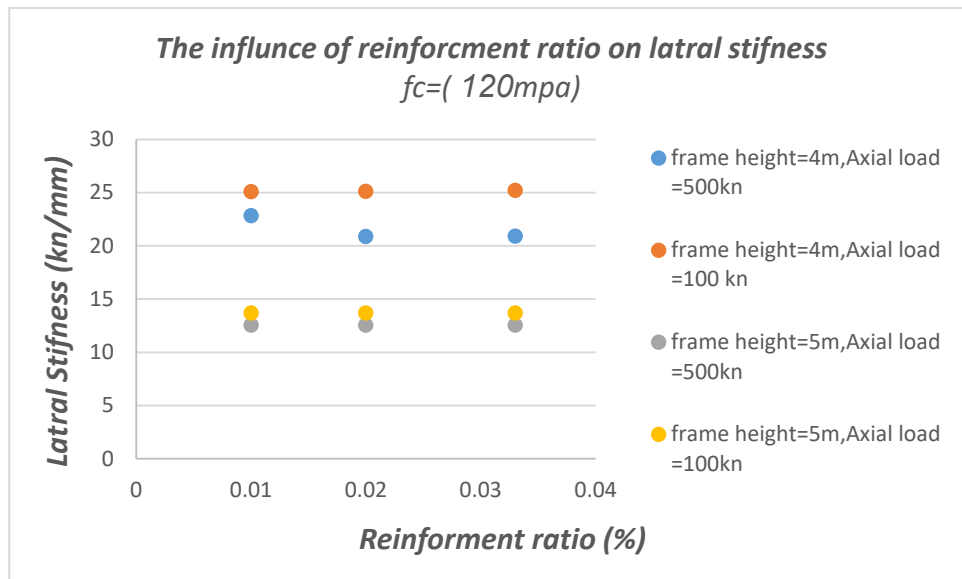
In addition, this result can be explained by the adoption of the strong-column weak beam concept in seismic design which was applied to this research models. The reinforcement percentage participated for column and considered fix for the beam, since the principle that used to calculate the effective stiffness is depend on the first yield whatever it reaches its yield first the concrete or the steel the first plastic hinged is expected to form at the beam section. Fig 14 illustrates the result of the influence of column reinforcement ratio on the lateral effective stiffness.

Figure 11

The Influence of Reinforcement Ratio on Structure Performance Lateral Stiffness (a)

$f_c=40\text{mpa}$, (b) $f_c=80\text{mpa}$, (c) $f_c=120\text{mpa}$.



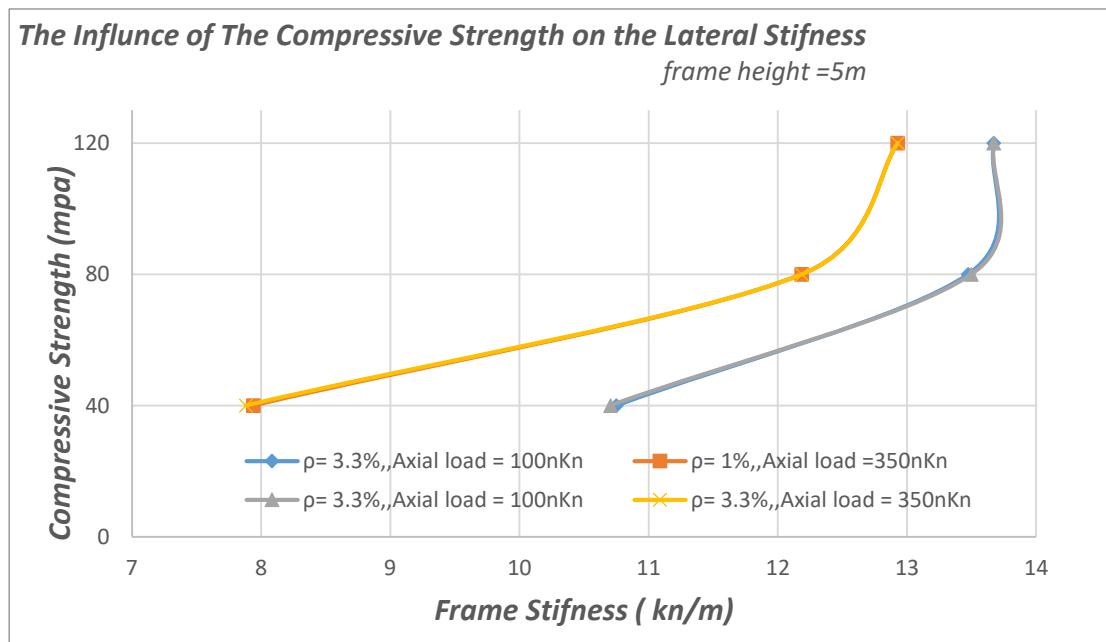
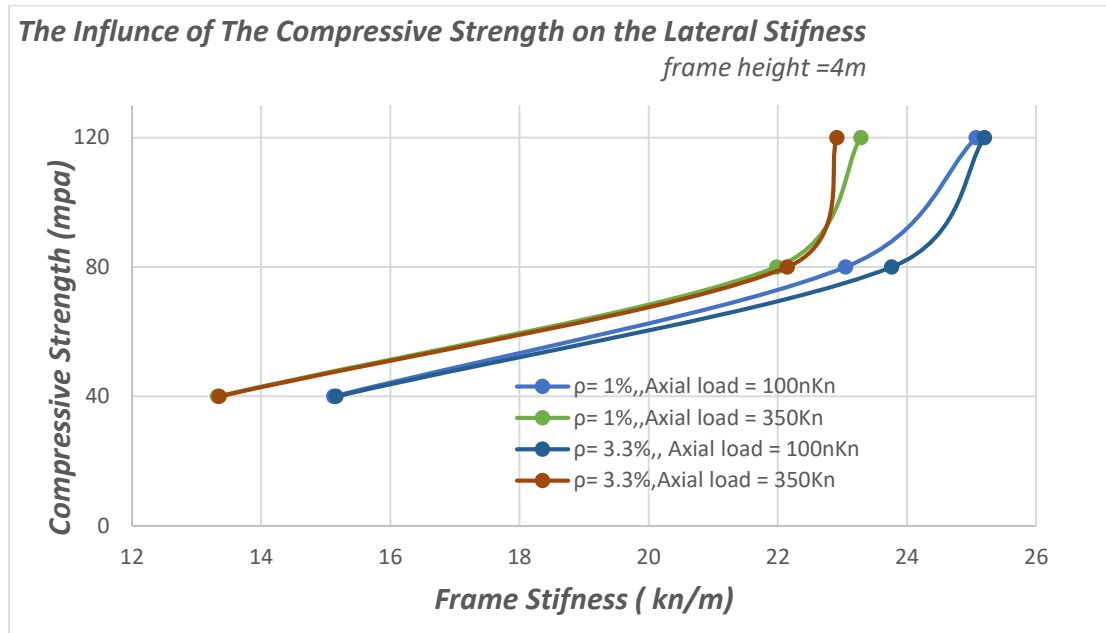


4.1.2 Compressive Strength

Unlike the reinforcement ratio, the compressive strength record a strong correlation with R values that exceed the 0.9 for all analysed frames with in the different reinforcement ratios and frame heights. Frames with higher compressive strength result in higher lateral stiffness. It is noticeable the increase of the compressive strength from 40mpa to 80map enhance the stiffness of the structure more than the enhancement of increasing it from 80 to 120 mpa, where at the first scenario the effective stiffness increased by approximately 9 kn/mm while in the second scenario the races is about just 1kn/mm in the case of the frame with 4m height. Similar trend observed for the 5m height frames.in addition, in the case of higher frame taking into consideration that increasing of the height diminish the stiffness, using high strength concrete can enhance the performance especially in the case of low axial load.

Figure 12

The Influence of Compressive Strength on Lateral Stiffness. (a) Frame height = 4m, (b) frame height = 5m



4.1.3 Column Height

Generally, the relevantly short column with the height of 4m exhibit very high stiffness in compare to the 5m high cases, in the lower scenario, the effective stiffness of a short column, standing at a height of 4 meters, is measured at 1.280times the stiffness of a frame with a height of 5 meters, where in the highest scenario the relevantly short column recorded 1.99 times the stiffness of the 5m height frame, this finding is consistent with the finding of kumar &yogendra (2010) of the effect of member length on the effective stiffness. The comparative between the both cases is presented in Table (4).

Table 3

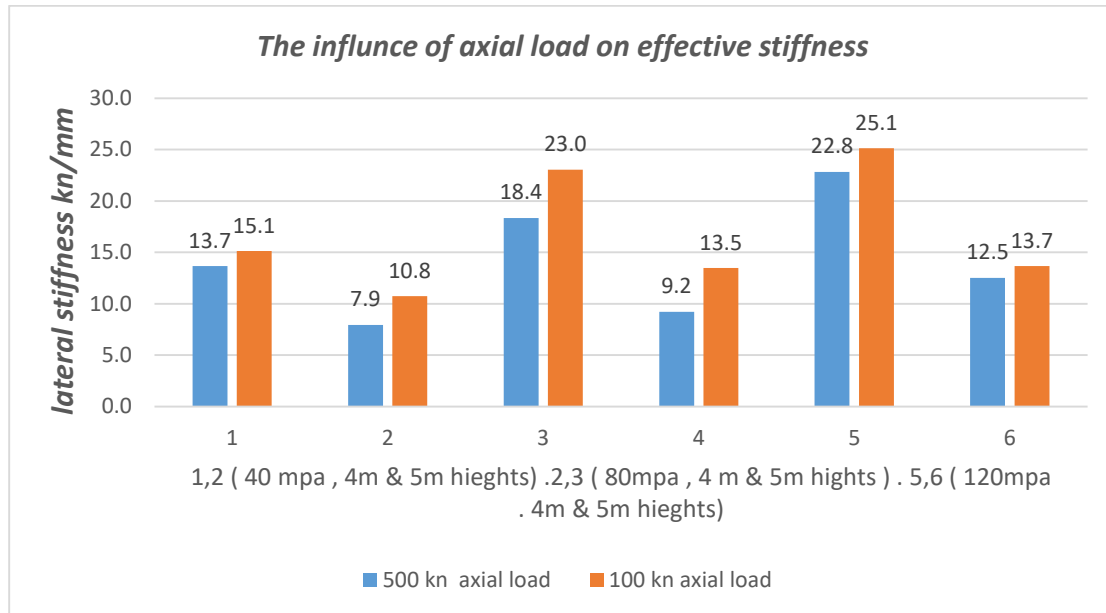
The Influence of the Columns Height on the Frame Performance

Compressive Strength (mpa)	Reinforcement Ratio	Applied Axial load (kn)	EI eff (Nonlinear) hiegt = 4M	EI eff (Nonlinear) hiegt = 5M	
[1]	[2]	[3]	[4]	[5]	[4]/[5]
40	0.01	350	13.32	7.94	1.68
		200	13.47	10.50	1.28
		100	15.12	10.75	1.41
	0.02	350	13.36	7.87	1.70
		200	20.78	10.69	1.94
		100	19.11	10.59	1.81
	0.033	350	13.35	7.88	1.69
		200	14.23	10.45	1.36
		100	15.16	10.70	1.42
	0.01	500	18.35	9.21	1.99
		350	21.98	12.19	1.80
		200	19.82	13.22	1.50
80	0.02	100	23.05	13.47	1.71
		500	18.32	9.40	1.95
		350	16.66	12.22	1.36
	0.033	200	19.75	12.58	1.57
		100	23.05	12.72	1.81
		500	20.54	11.28	1.82
	0.01	350	22.15	12.19	1.82
		200	23.65	13.24	1.79
		100	23.76	13.50	1.76
	0.01	500	18.35	12.53	1.46
		350	23.29	12.93	1.80

120	0.02	200	24.45	13.53	1.81
		100	25.07	13.67	1.83
		500	20.87	12.53	1.67
		350	22.99	12.93	1.78
		200	24.61	13.53	1.82
	0.033	100	25.12	13.67	1.84
		500	20.90	12.53	1.67
		350	22.92	12.93	1.77
		200	24.54	13.53	1.81
		100	25.20	13.67	1.84
			Minimum	1.28	
			Maximum	1.99	

4.1.4 Axial Load Effect

The axial load is the most influence parameter that effect the performance of the concrete frames under lateral load, regardless the value of all studied parameters the increase of the axial load decreases the lateral stiffness of concrete frames under lateral load, the influence of this factor is significantly affect the global stiffness of the structure as well as it is significantly affect the flexural stiffness of the members. This finding consistent with claim that the flexural stiffness affects the performance of the structure where all the previous studies from the literature not just admit the influence of the axial load but their all the of the models are depend on the axial load ratios. Statistical correlation analysis shows a coefficient of over 0.9 for the most cases. Appendix F shows the details of the statistical analysis.

Figure 13*Axial Load Effect on Lateral Stiffness*

4.2 The Comparison Between the Performance of Structure Using Simplified and Non-Linear Analysis Method of Flexural Stiffness Estimation

Based on the Analysis results it has found that the behaviour of structure using simplified analysis method result in lower lateral stiffness (lower performance) in the all cases of different using the parameters of this study. in another words it's always safe to use the simplified method (representing by $0.7EI_g$ for columns $0.35EI_g$ for beams) in the case of frame analysis under lateral load, this it can be noticed clearly in fig 13 a&b, it's also noted that using the simplified method leads to very similar results (coefficient of variation = 11.740) because its calculated depend of the constant ratio of $E_c I_g$. the first nine cases (all with $f_c = 40$ mpa) for the both short and long frames are exhibit the least effective stiffness this because have the modulus of elasticity of normal concrete is lower than the modulus of elasticity of the high strength concrete while the value of the moment of inertia is constant because only one section is adopted for all cases (25*60 for the column and 20*50 for the beam). It's also noticeable that for the cases between 10 and 22 (cases with

80 mpa compressive strength) each four cases started from relevantly lower effective stiffness and increased slightly until the fourth case. this trend continues three times for the cases from 10 to 13, 14 to 17 and from 18 to 22, this light changed explained by the decrease of the applied axial load and it will explain more in the next in 4.2.4. in contrast to the simplified method, the non-linear analysis shows wide range of changes between the analysed cases in compare with the simplified method where it takes into consideration the whole different parameters that affect the effective stiffness (with coefficient of variation = 26.71).

Table 3 list the results of the analysis for all considered cases. Column 8 present the percentage of the (EI_{eff}) calculated from non-linear analysis to (EI_{eff}) that measured from simplified analysis method. All percentages are range between 1.12 to 2.21. Although the 1.12 can be consider acceptable to provide a safety ranged but on the other hand the highest limit for percentage is considered conservative. The average presented percentage of the using non-linear analysis to simplified method is 1.36, 1.44 and 1.57 for frames with compressive strength of 40, 80 and 120 map.

Table 4

Descriptive Statistics for the Two Analysis Methods

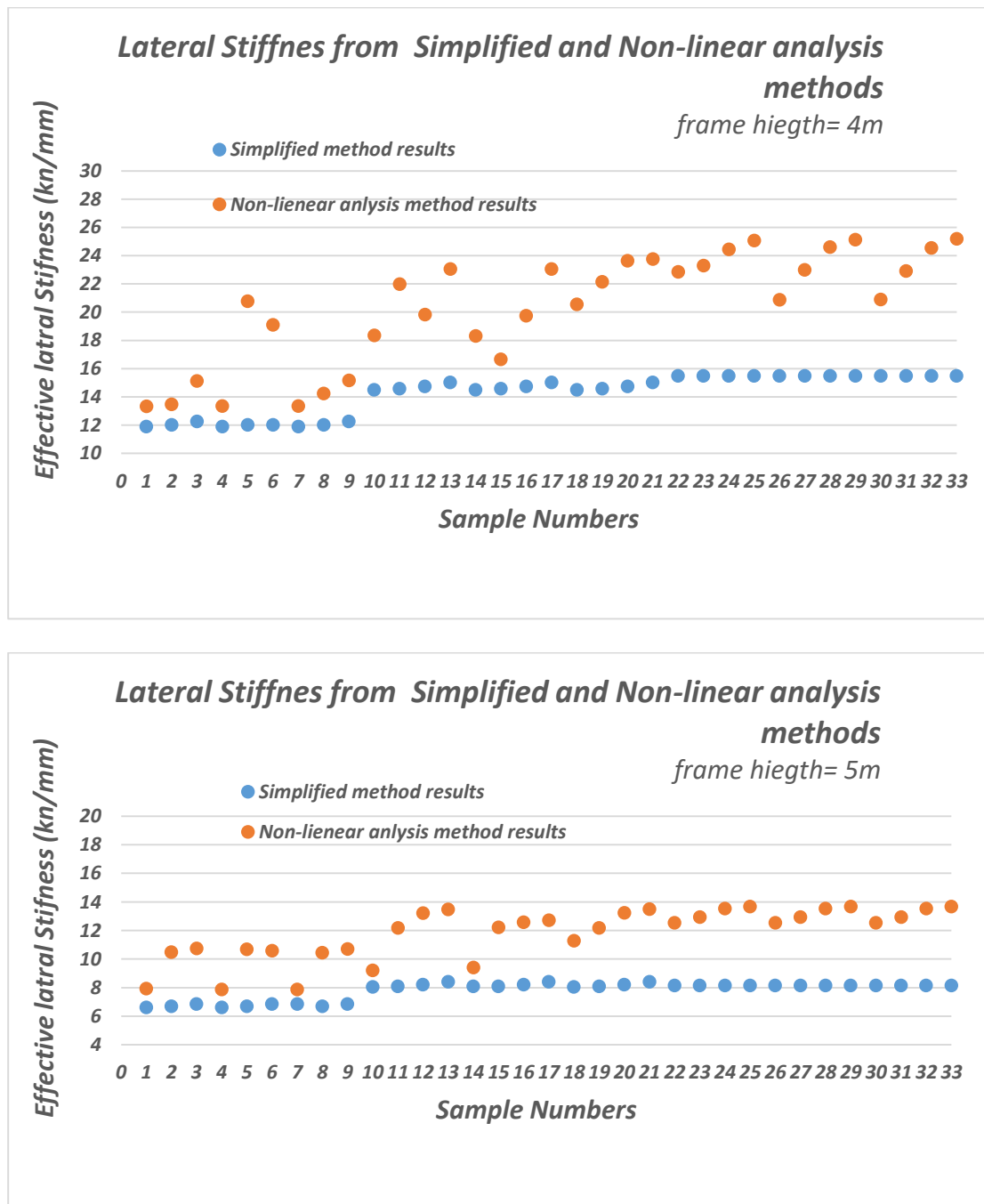
Cas e (1)	Reinforce ment (2)	Applied Axial load (3)	Compress ive Strength (4)	Height (5)	EI_{eff} (Simplified) (6)	EI_{eff} (Nonlinear) (7)	EI_{effnon} / $EI_{effsimp}$ (8)
No	Ratio	(kn)	(mpa)	(m)	(kn/mm)	(kn/mm)	
1	0.01	350	40	4	11.88	13.32	1.12
2	0.01	200	40	4	12.01	13.47	1.12
3	0.01	100	40	4	12.25	15.12	1.23
4	0.02	350	40	4	11.88	13.36	1.12
5	0.02	200	40	4	12.01	20.78	1.59
6	0.02	100	40	4	12.01	19.11	1.73
7	0.033	350	40	4	11.88	13.35	1.12
8	0.033	200	40	4	12.01	14.23	1.18

9	0.033	100	40	4	12.25	15.16	1.24
10	0.01	350	40	5	6.60	7.87	1.19
11	0.01	200	40	5	6.69	10.50	1.57
12	0.01	100	40	5	6.85	15.16	2.21
13	0.02	350	40	5	6.60	7.87	1.19
14	0.02	200	40	5	6.69	10.69	1.60
15	0.02	100	40	5	6.85	10.59	1.54
16	0.033	350	40	5	6.85	7.88	1.15
17	0.003	200	40	5	6.69	10.69	1.60
18	0.003	100	40	5	6.85	10.70	1.56
19	0.01	500	80	4	14.50	18.35	1.27
20	0.01	350	80	4	14.57	21.98	1.51
21	0.01	200	80	4	14.73	19.82	1.35
22	0.01	100	80	4	15.02	23.05	1.53
23	0.02	500	80	4	14.50	18.32	1.26
24	0.02	350	80	4	14.57	16.66	1.14
25	0.02	200	80	4	14.73	19.75	1.34
26	0.02	100	80	4	15.02	23.05	1.53
27	0.033	500	80	4	14.50	20.54	1.42
28	0.033	350	80	4	14.57	22.15	1.52
29	0.033	200	80	4	14.73	23.65	1.61
30	0.033	100	80	4	15.02	23.76	1.58
31	0.01	500	80	5	8.04	9.21	1.14
32	0.01	350	80	5	8.09	12.19	1.51
33	0.01	200	80	5	8.20	13.22	1.61
34	0.01	100	80	5	8.40	13.47	1.60
35	0.02	500	80	5	8.09	9.40	1.16
36	0.02	350	80	5	8.09	12.22	1.51
37	0.02	200	80	5	8.20	12.58	1.53
38	0.02	100	80	5	8.40	12.72	1.51
39	0.033	500	80	5	8.04	11.28	1.40
40	0.033	350	80	5	8.09	12.19	1.51
41	0.033	200	80	5	8.20	13.24	1.61
42	0.033	100	80	5	8.40	13.50	1.61
43	0.01	500	120	4	14.50	18.35	1.27
44	0.01	350	120	4	15.48	23.29	1.50
45	0.01	200	120	4	15.48	24.45	1.58
46	0.01	100	120	4	15.48	25.07	1.62
47	0.02	500	120	4	15.47	20.87	1.35
48	0.02	350	120	4	15.47	22.99	1.49
49	0.02	200	120	4	15.47	24.61	1.59
50	0.02	100	120	4	15.47	25.12	1.62
51	0.033	500	120	4	15.47	20.90	1.35
52	0.033	350	120	4	15.47	22.92	1.48
53	0.033	200	120	4	15.47	24.54	1.59
54	0.033	100	120	4	15.47	25.20	1.63
55	0.01	500	120	5	8.14	12.53	1.54
56	0.01	350	120	5	8.14	12.93	1.59

57	0.01	200	120	5	8.14	13.53	1.66
58	0.01	100	120	5	8.14	13.67	1.68
59	0.02	500	120	5	8.15	12.53	1.54
60	0.02	350	120	5	8.14	12.93	1.59
61	0.02	200	120	5	8.14	13.53	1.66
62	0.02	100	120	5	8.14	13.67	1.68
63	0.033	500	120	5	8.15	12.53	1.54
64	0.033	350	120	5	8.14	12.93	1.59
65	0.033	200	120	5	8.14	13.53	1.66
66	0.033	100	120	5	8.14	13.67	1.68
					Minimum	6.60	7.87
					Maximum	15.48	25.20
					Average	11.00	16.10
					Standard deviation	3.43	5.17
					Variation	11.74	26.71
					confection		

Figure 14

Lateral Stiffness Results Based on Simplified and Non-Linear Analysis Methods (a) frame height = 4m, (b) frame height = 5m



Chapter 5: Conclusion and Recommendation

5.1 Conclusion

The non-linear static analysis has been conducted to 66 concrete frames using 4 different parameters, Frame height (4 and 5m), compressive strength (40, 80, 120mpa), column reinforcement ratio (1%, 2% and 3%) axial load (100, 200, 350, 500kn). the analysis results are discussed on chapter 4 and can be conclude as follow:

5.1.1 The Influence of the Study Parameters on the Structural Performance

- The majority of parameters influencing the flexural stiffness of concrete elements bear substantial significance in determining the overall performance of the structure. Consequently, the utilization of an inaccurate effective flexural stiffness (EI_{eff}) could result in suboptimal design, leading to an analysis that fails to accurately represent the genuine performance of the structure.
- Reinforced concrete frames experience notable influence from both axial loads and frame height. An elevation in axial load tends to diminish lateral stiffening, while an increase in frame height similarly contributes to a reduction in lateral stiffness significantly.
- The reinforcement concrete frames are significantly affected by compressive strength where the lateral stiffness increase by the increasing of the compressive strength. This effect becomes more pronounced, particularly under higher axial loads. Additionally, this effect is more pronounced when employing high-strength concrete in comparison to normal-strength concrete, and is even more evident when increasing the strength from 80 to 120 mpa.
- The reinforcement ratios do not record noticeable effect of lateral stiffness; this is not inconsistent with its effect on the flexural stiffness for individual elements. The

rationale behind this lies in the implementation of the "weak beam strong column" concept, which anticipates that the initial yield will occur within the beam

5.1.2 The Comparison Between the Performance of Structure Using Simplified and Non-Linear Analysis Method of Flexural Stiffness Estimation

- Based on this study using simplified methods are result in a conservative performance and it 'will be better to use to used rigorous analysis or at least using the second proposal by ACI -318-19 Table 6.6.3.1.1(a).
- There is an observation of the relation between the compressive strength and evaluation of using simplified analysis method, where by increasing the compressive strength, the results show this method getting more conservatively.

In conclusion, the utilization of high-strength concrete improves the performance of reinforced frame structures. However, heightened column dimensions and increased axial loads tend to reduce the structural stiffness. Assumptions of $0.7 EI_g$ for columns and $0.35 EI_g$ for beams are considered safe yet conservative.

5.2 Recommendation

- Further analysis is recommended to calculate the actual flexural stiffness for each reinforced concrete element separately using the moment-curvature curve for the moment equivalent to the yield point from load-deformation curve.
- Further analysis is recommended to evaluate the simplified method in post yielded point within the range of both damage control and life safety performance.
- Further analysis using different stress-strain models to detect the nonlinear behaviour and the corresponding effective stiffness for each material modal is highly recommended, where this may lead to capture different performance of the structure.

References

- ACI Committee. (2008). Building code requirements for structural concrete (ACI 318-08) and commentary. American Concrete Institute.
- Khuntia, M., & Ghosh, S. K. (2004). Flexural stiffness of reinforced concrete columns and beams: analytical approach. *Structural Journal*, 101(3), 351-363.(Flexural Stiffness of Reinforced Concrete Columns and Beams: Analytical Approach)
- Khuntia, M., & Ghosh, S. K. (2004). Flexural stiffness of reinforced concrete columns and beams: experimental verification. *Structural Journal*, 101(3), 364-374.(Flexural Stiffness of Reinforced Concrete Columns and Beams: Experimental Verification)
- Mehanny, S. S., Kuramoto, H., & Deierlein, G. G. (2001). Stiffness modeling of reinforced concrete beam-columns for frame analysis. *Structural Journal*, 98(2), 215-225.(Stiffness Modeling of Reinforced Concrete Beam-Columns for Frame Analysis).
- Das, S., Mansouri, I., Choudhury, S., Gandomi, A. H., & Hu, J. W. (2021). A Prediction Model for the Calculation of Effective Stiffness Ratios of Reinforced Concrete Columns. *Materials*, 14(7), 1792.(<https://doi.org/10.3390/ma14071792>).
- Kumar, R., & Singh, Y. (2010). Stiffness of Reinforced Concrete Frame Members for Seismic Analysis. *ACI Structural Journal*, 107(5).
- Elwood, K. J., & Eberhard, M. O. (2009). Effective Stiffness of Reinforced Concrete Columns. *ACI Structural Journal*, 106(4).
(<http://www.concrete.org/PUBS/JOURNALS/SJHOME.ASP>)
- MOREIRA, L., & MARTINS, C. (2018). Low-rise structures in reinforced concrete: approximation of material nonlinearity for global stability analysis. *Revista*

IBRACON de Estruturas e Materiais, 11, 01 25. (<https://doi.org/10.1590/S1983-41952018000100002>)

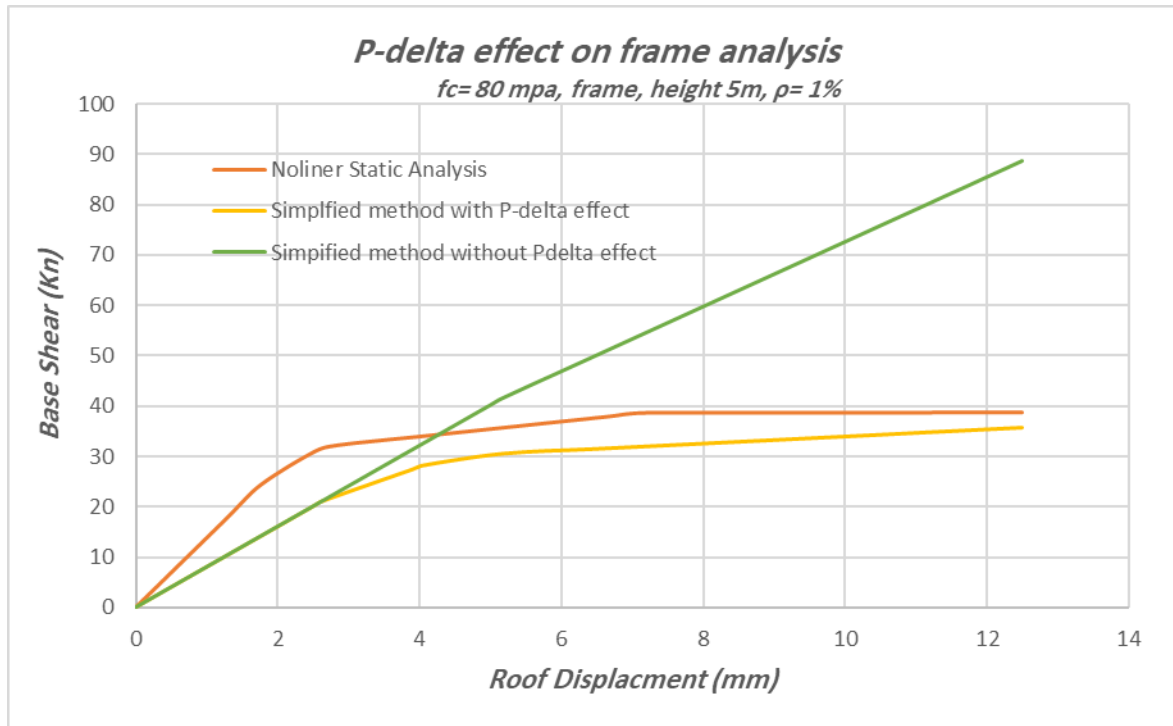
- Alavi-Dehkordi, S., Mostofinejad, D., & Alaei, P. (2019). Effects of high-strength reinforcing bars and concrete on seismic behavior of RC beam-column joints. *Engineering Structures*, 183, 702-719.
(<https://doi.org/10.1016/j.engstruct.2019.01.019>)
- Lokuge, W. P., Sanjayan, J. G., & Setunge, S. (2005). Stress–strain model for laterally confined concrete. *Journal of Materials in Civil Engineering*, 17(6), 607-616.([https://doi.org/10.1061/\(ASCE\)0899-1561\(2005\)17:6\(607](https://doi.org/10.1061/(ASCE)0899-1561(2005)17:6(607))
- Popovics, S. (1973). A numerical approach to the complete stress-strain curve of concrete. *Cement and concrete research*, 3(5), 583-599.
([https://doi.org/10.1016/0008-8846\(73\)90096-3](https://doi.org/10.1016/0008-8846(73)90096-3))
- Tsai, W. T. (1988). Uniaxial compressional stress-strain relation of concrete. *Journal of Structural Engineering*, 114(9), 2133–2136
([https://doi.org/10.1061/\(ASCE\)0733-9445\(1988\)114:9\(2133](https://doi.org/10.1061/(ASCE)0733-9445(1988)114:9(2133))
- Carreira, D. J., & Chu, K. H. (1985, November). Stress-strain relationship for plain concrete in compression. In *Journal Proceedings* (Vol. 82, No. 6, pp. 797-804).([https://doi.org/10.1061/\(ASCE\)0899-1561\(1999\)11:1\(211\)](https://doi.org/10.1061/(ASCE)0899-1561(1999)11:1(211))).
- Hsu, L. S., & Hsu, C. T. (1994). Complete stress—strain behaviour of high-strength concrete under compression. *Magazine of concrete research*, 46(169), 301-312.(<https://doi.org/10.1680/mac.1994.46.169.301>).
- Wee, T. H., Chin, M. S., & Mansur, M. A. (1996). Stress-strain relationship of high-strength concrete in compression. *Journal of materials in civil engineering*, 8(2), 70-76.([https://doi.org/10.1061/\(ASCE\)0899-1561\(1996\)8:2\(70](https://doi.org/10.1061/(ASCE)0899-1561(1996)8:2(70)) .

- Razvi, S., & Saatcioglu, M. (1999). Confinement model for high-strength concrete. *Journal of Structural Engineering*, 125(3), 281-289.([https://doi.org/10.1061/\(ASCE\)0733-9445\(1999\)125:3\(281\)](https://doi.org/10.1061/(ASCE)0733-9445(1999)125:3(281))).
- Baduge, S. K., Mendis, P., & Ngo, T. (2018). Stress-strain relationship for very-high strength concrete (> 100 MPa) confined by lateral reinforcement. *Engineering Structures*, 177, 795-808.(<https://doi.org/10.1016/j.engstruct.2018.08.008>).
- Shehata, I. A., Shehata, L. C., & Mattos, T. S. (2000). Stress-strain curve for the design of high-strength concrete elements. *Materials and Structures*, 33, 411-418.(<https://doi.org/10.1007/BF02480659>).
- Kmiecik, P. A., & Kamiński, M. (2011). Modelling of reinforced concrete structures and composite structures with concrete strength degradation taken into consideration. *Archives of civil and mechanical engineering*, 11(3), 623-636.([https://doi.org/10.1016/S1644-9665\(12\)60105-8](https://doi.org/10.1016/S1644-9665(12)60105-8)).
- Deierlein, G. G., Reinhorn, A. M., & Willford, M. R. (2010). Nonlinear structural analysis for seismic design. *NEHRP seismic design technical brief*, 4, 1-36.
- Krawinkler, H. (1996, October). Pushover analysis: why, how, when, and when not to use it. In *Proceedings of the 65th Annual Convention of the Structural Engineers Association of California* (pp. 17-36).
- Pekelnicky, R., Engineers, S. D., Chris Poland, S. E., & Engineers, N. D. (2012). ASCE 41-13: Seismic evaluation and retrofit rehabilitation of existing buildings. *Proceedings of the SEAOC*.
- Slevitch, L. (2011). Qualitative and quantitative methodologies compared: Ontological and epistemological perspectives. *Journal of quality assurance in hospitality & tourism*, 12(1), 73-81.
(<https://doi.org/10.1080/1528008X.2011.541810>).

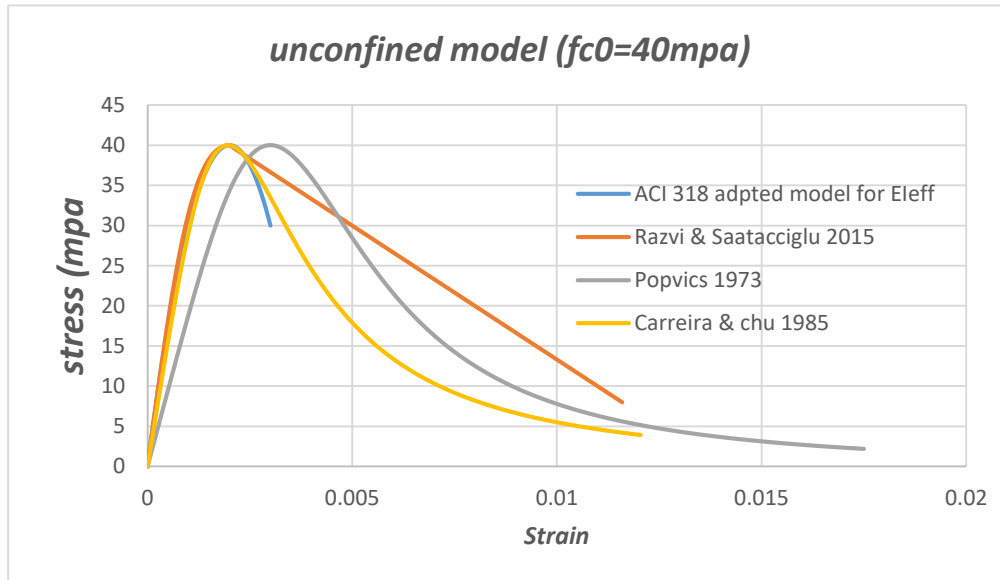
- Pednekar, S. C., Chore, H. S., & Patil, S. B. (2015). Pushover analysis of reinforced concrete structures. *International Journal of Computer Applications*, 975, 8887.
- Abhilash, R. and Biju, V., 2010. Effect of lateral load patterns in pushover analysis. Saisaran, G.S., Prasad, V.Y.D. and Das, T.V., 2016.
- Saisaran, G. S., Prasad, V. Y. D., & Das, T. V. (2016). Push Over Analysis for Concrete Structures at Sesimic Zone-3 using Etabs Software. *International Journal of Engineering Research*, 5(03).(DOI:10.17577/IJERTV5IS031262)
- Oni, P. B., & Vanakudre, S. B. (2013). Performance based evaluation of shear walled RCC Building by Pushover analysis. *International Journal of Modern Engineering Research (IJMER)*, 3(4).
- Pierre, A. J., & Hidayat, I. (2020, February). Seismic performance of reinforced concrete structures with pushover analysis. In *IOP Conference Series: Earth and Environmental Science* (Vol. 426, No. 1, p. 012045). (DOI 10.1088/17551315/426/1/012045)

Appendices

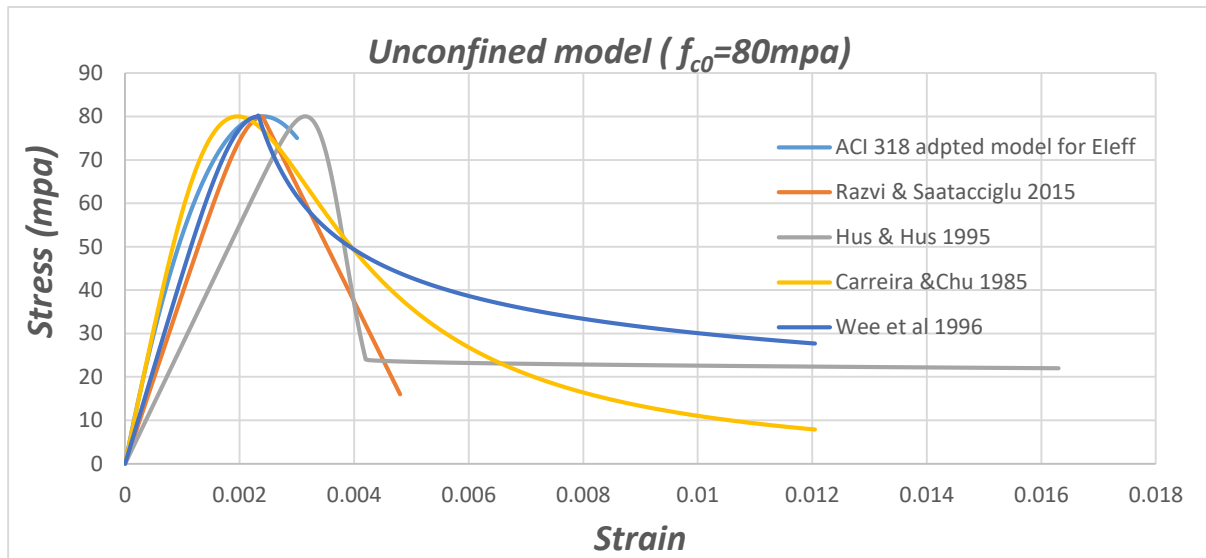
Appendix A: The P-Delta Effect on Structure Stiffness



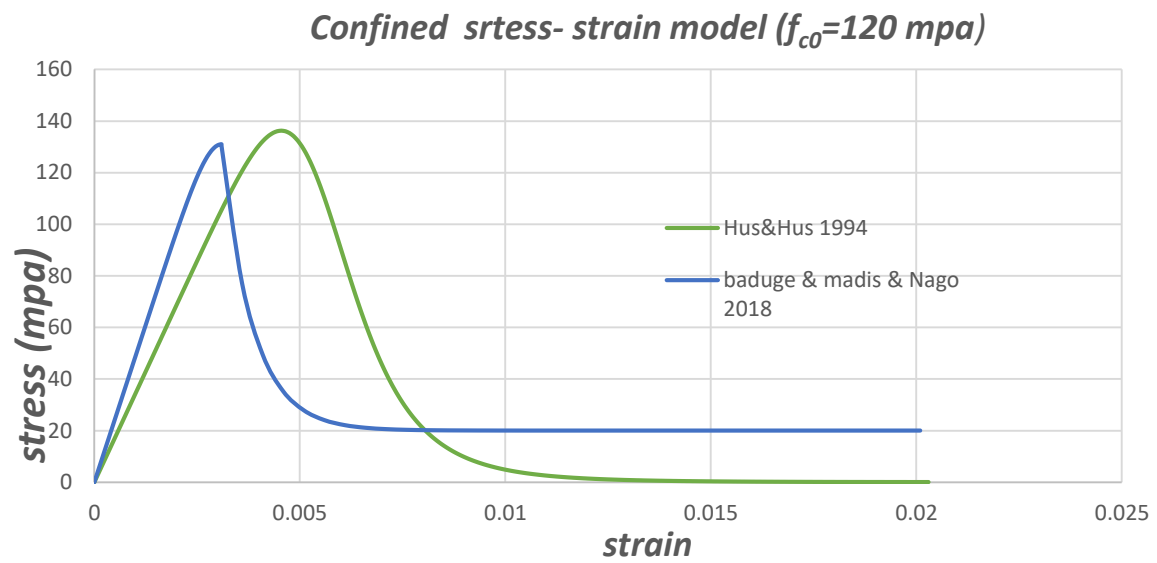
Appendix B: The Comparison between the Stress-Strain Models Under Compression ($f_c=40\text{mpa}$)



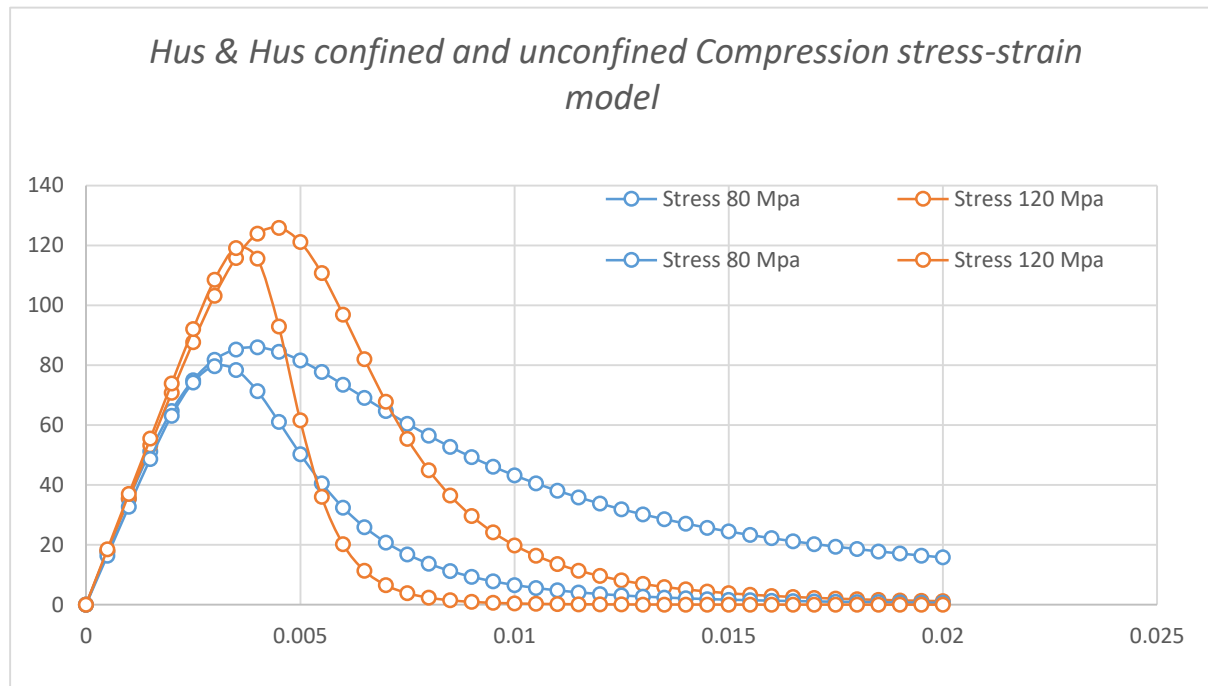
Appendix C: The Comparison between the Stress-Strain Models Under Compression($f_c=80\text{mpa}$)



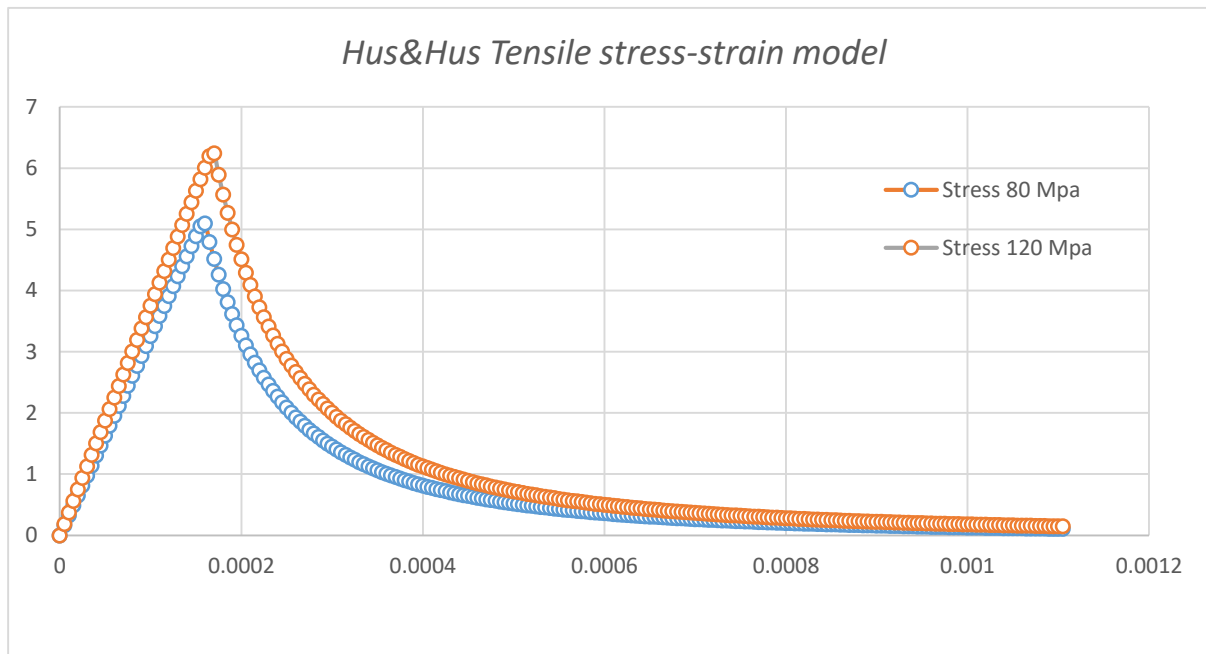
Appendix D: The Comparison Between the Stress-Strain Models Under Compression ($f_c=120\text{mpa}$)



Appendix D: Compression Stress-Strain Models that used for Analysis



Appendix E: Tension Stress-Strain Models that used for Analysis



Appendix F: Correlation between Applied Axial Load and Effective Stiffness

Reinforcement Ratio	fc (mpa)	Height (m)	Applied Axial load (kn)	EI eff (Nonlinear) (kn/mm)	correlation analysis results	
0.01	40	4	350	13.32468	Column 1	Column 2
0.01	40	4	200	13.47121	Column 1	1
0.01	40	4	100	15.12331	Column 2	- 0.84451 1
0.02	40	4	350	13.36126	Column 1	Column 2
0.02	40	4	200	20.78	Column 1	1
0.02	40	4	100	19.10978	Column 2	- 0.81092 1
0.033	40	4	350	13.35026	Column 1	Column 2
0.033	40	4	200	14.23124	Column 1	1
0.033	40	4	100	15.16111	Column 2	- 0.99149 1
0.01	40	5	350	7.939826	Column 1	Column 2
0.01	40	5	200	10.49506	Column 1	1
0.01	40	5	100	10.75054	Column 2	- 0.94722 1
0.02	40	5	350	7.8711	Column 1	Column 2
0.02	40	5	200	10.69175	Column 1	1
0.02	40	5	100	10.58632	Column 2	- 0.90406 1
0.033	40	5	350	7.882605	Column 1	Column 2
0.003	40	5	200	10.44902	Column 1	1
0.003	40	5	100	10.70457	Column 2	- 0.94711 1
0.01	80	4	500	18.35197	Column 1	Column 2
0.01	80	4	350	21.98305	Column 1	1
0.01	80	4	200	19.82362	Column 2	- 0.70516 1
0.01	80	4	100	23.0491		
0.02	80	4	500	18.31527	Column 1	Column 2

0.02	80	4	350	16.65849	Column 1	1	
0.02	80	4	200	19.74787	Column 2	-	1
0.02	80	4	100	23.0491			
					Column 1	Column 2	
0.033	80	4	500	20.54393			
0.033	80	4	350	22.14753	Column 1	1	
0.033	80	4	200	23.64777	Column 2	-	1
0.033	80	4	100	23.76			
					Column 1	Column 2	
0.01	80	5	500	9.209239			
0.01	80	5	350	12.18554	Column 1	1	
0.01	80	5	200	13.22212	Column 2	-	1
0.01	80	5	100	13.47316			
					Column 1	Column 2	
0.02	80	5	500	9.402347			
0.02	80	5	350	12.21867	Column 1	1	
0.02	80	5	200	12.57965	Column 2	-	1
0.02	80	5	100	12.71672			
					Column 1	Column 2	
0.033	80	5	500	11.27634			
0.033	80	5	350	12.18716	Column 1	1	
0.033	80	5	200	13.24008	Column 2	-	1
0.033	80	5	100	13.49826			
					Column 1	Column 2	
0.01	80	4	500	18.35197			
0.01	120	4	350	23.28655	Column 1	1	
0.01	120	4	200	24.45261	Column 2	-	1
0.01	120	4	100	25.07252			
					Column 1	Column 2	
0.02	120	4	500	20.87289			
0.02	120	4	350	22.99474	Column 1	1	
0.02	120	4	200	24.61351	Column 2	-	1
0.02	120	4	100	25.1238			
					Column 1	Column 2	
0.033	120	4	500	20.89941			
0.033	120	4	350	22.92	Column 1	1	

0.033	120	4	200	24.54281	Column 2	- 0.99019	1
0.033	120	4	100	25.20138			
0.01	120	5	500	12.53171	Column 1	Column 2	
0.01	120	5	350	12.92886	Column 1	1	
0.01	120	5	200	13.53348	Column 2	- 0.99019	1
0.01	120	5	100	13.67264			
0.02	120	5	500	12.53171	Column 1	Column 2	
0.02	120	5	350	12.92886	Column 1	1	
0.02	120	5	200	13.53348	Column 2	- 0.99019	1
0.02	120	5	100	13.67264			
0.033	120	5	500	12.53171	Column 1	Column 2	
0.033	120	5	350	12.92886	Column 1	1	
0.033	120	5	200	13.53348	Column 2	- 0.99019	1
0.033	120	5	100	13.67264			