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APPLICATION OF SHAPE MEMORY ALLOY IN REINFORCED CONCRETE STRUCTURE

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by

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17530

Dissertation submission in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Civil Engineering)

SEPTEMBER 2016

Universiti Teknologi PETRONAS,

32610, Bandar Seri Iskandar,

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Project dissertation submitted to the
Civil Engineering Programme
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Approved by,

____

(Dr. Ehsan Nikbakht Jarghouyeh)

UNIVERSITI TEKNOLOGI PETRONAS
BANDAR SERI ISKANDAR, PERAK
September 2016

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MUHAMMAD AMIN BIN MD DESA

ABSTRACT

The study on application of Shape Memory Alloys (SMA) in had been done previously with different methods. This new material have the unique ability to sustain large deformations and returned to their original shape upon stress applied for Superelastic SMA or by heating the SMA for Shape Memory Effect Abdulridha, Palermo, Foo and Vecchio(2013)to further analyse the performance towards the application of the SMA bars in reinforced concrete structure as a to help enhance reinforce concrete into resisting lateral load and towards providing more valuable information for prediction of the performance behaviour of SMAs towards modern structure. This research is to compare the performance between segmental column reinforced with Mild Steel, Superelastic SMA and Niti Martensitic SMA longitudinal bars. The bars are used are longitudinal bars located at bottom of the column to resist the lateral deflection and help in gap closing effect. The method is to modelled numerically and analyse the segmental column reinforced with superelastic SMA and Niti Martensitic SMA by using ANSYS (2009) as a finite element analysis. The segmental column with both SMAs will be test towards lateral deflection to test for SMA behaviour. Further to study the SMA behaviour the different post tension effect also used. The higher elasticity effect show in superelastic SMA due to the material behaviour and stiffness. The model with SMA capable of achieving small residual displacement event after been exposed to large deflection compare to other. This helps in closing gap and opening in between segment. Crack formation also less in model with SMA due to the highly elastic properties. Effect of different post tension stress on the model is slightly significant. It helps increase the column lateral resistivity however, reduces the column effectiveness in permanent deformation.

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Every project big or small is successful largely due to the effort of a number of wonderful people who have always given their valuable advice or lent a helping hand. I sincerely appreciate the inspiration, support and guidance of all those people who have been instrumental in making this project a success.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Reinforced concrete structures mainly are composite part of concrete partially and reinforcement bar to allow for tension and additional tension behaviour of structural members. Recently, a new group of alloys has been emerged in the research community and known as Shape Memory Alloys (SMAs). This new material have the unique ability to sustain large deformations and returned to their original shape upon stress applied for Superelastic SMA or by heating the SMA for Shape Memory Effect SMA Abdulridha, Palermo, Foo and Vecchio (2013). These show there are two types of SMA bars which is Superelastic SMA bars and Niti Martensitic SMA bars DesRoches et al. (2004) appointed that towards resisting in both tension and compression strains the bar type SMAs provides a large inelastic deformation without significant loss in strength. For the Martensitic type SMAs which has the ability to recover residual strain by heating or known as shape memory effects. Finally, SMAs also has the unique ability to posses high damping capacity in both state Austenite and Martensite with higher capacity in Martensitic phase. This is due to the stress induced transformation in Martensitic under applicants of external loads. This resultant in increment amount of research in application of SMAs in seismic resistance structure. Due to the uniqueness ability of this material this study was conducted to further analyse the performance towards the application of the SMA bars in reinforced concrete structure as a reinforcement replacement material and towards providing more valuable information for prediction of the performance behaviour of SMAs towards modern structure.

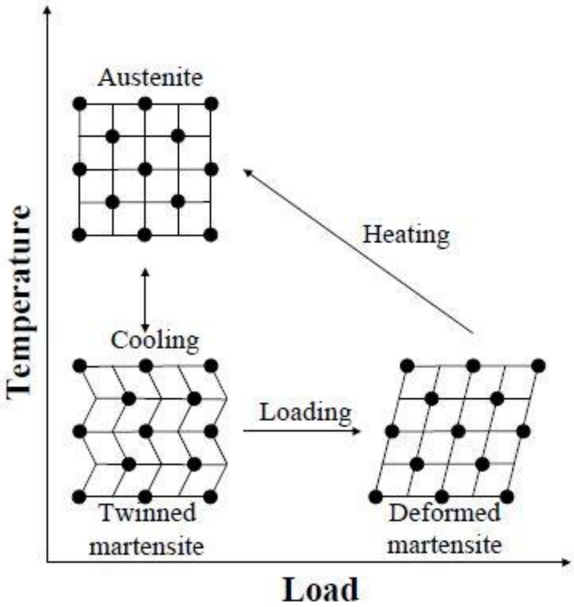


Figure 1.1: Different Temperatures and Loads effects SMA phases

1.2 Problem Statement

The use of conventional cast in situ RC column resulting in very large residual displacement due to large lateral loading for instance the earthquake load. This increase the demand of column with the high self-centring effect to help maintain the functionality of the column. Few researchers had investigate the effective design improvements for the column. With the application of the Shape memory alloy longitudinal reinforcement bar at the bottom of the plastic hinge area it can reduce the residual displacement and increase the energy dissipation of the column. Besides that, with the addition of segmental column combined with post tensioning tendon the self-centring effect also can be further increased.

1.3 Objectives and Scope of Study

Based on problem states in previous subtopics, few objectives and research scope are being identified in order to evaluate the project feasibility to be done within FYP 1 & FYP 2. The objectives of this study are:

1. To investigate the performance of shape memory alloy in precast post tensioned segmental column as hybrid reinforcement at the inelastic region of pier column towards lateral resistance compare to conventional normal reinforcement.

2. To determine the effect of different initial post-tension strength in precast post tensioned segmental column reinforced with SMA and conventional reinforcement.

3. To compare the performance of Superelastic SMA and Niti Martensitic SMA.

CHAPTER 2

LITERATURE REVIEW

To achieve the desired objective, suitable literature and method of work must be identified based on past research related to this topic. The literature are critically analyzed to relate one work and ideas to the other.

2.1 Superelastic Shape Memory Alloy

In recent quarter of 20^{th} century, the research industry had been introduced to smart materials as the technologies in engineering of materials are blooming. Smart materials is known as a materials that are capable to changes its mechanical properties in a controllable manner due to the material surrounding environment or external condition. One of the emerging smart materials are shape memory alloys (SMA) which has the capability to return to its originals shape upon heated or by removing of applied stress. Recently, concrete structures had been evolved along with modern technology in order to utilize the potential of concrete structures due to the exposure to potential extreme hazardous environment. Various research had been undergone to study the effect and materials behavior of the SMAs in reinforced concrete structures.

2.1.2 Material Properties of Shape Memory Alloys

According to Song, Ma, & Li, (2006) the performance of Nitinol SMAs has two unique properties which is Shape Memory Effects (SME) and Superelasticity. The SME behaviour refers to the phenomenon that the SMAs able to return to its original predetermined shape upon heating to certain temperature. On the other hand, the superelasticity referring to the phenomenon that SMAs can undergo a large inelastic deformation and recover its shape after unloading at 0% residual stress. Those resulting in the reversible phase of the SMAs transformation.

This properties was resulting from SMAs transformation phase which consists of two crystal phase. The austenite is the stronger phase and stable in high temperature while the weaker martensite phase was stable at low temperature. The austenite has a centered cubic structured on the other hand, the martensite has the parallelogram structure having up to 24 variations. When external stress are applied to SMAs in martensite phase, they will deformed with de-twinned mechanism, which transform different martensite variations to the particular that able to accommodate to the maximum elongation. Due to its weak parallelogram structure, the martensite can easily deformed. However, the austenite phase only has one orientation and relatively strong resistance to external stress.(G Song et al. 2006).

A.Abdulridha et al. in their study agree to *G Song et al.* of that behavior of SMA during reverse transformation from Martensite to Austenite , which in Austenite that the SMA returns to its original undeformed shape at zero stress. At large strains, the material strain hardens due to the elastic response of the stress induced Martensite phase. The initial unloading response is linear followed by a sharp recovery of strains at almost constant stress.

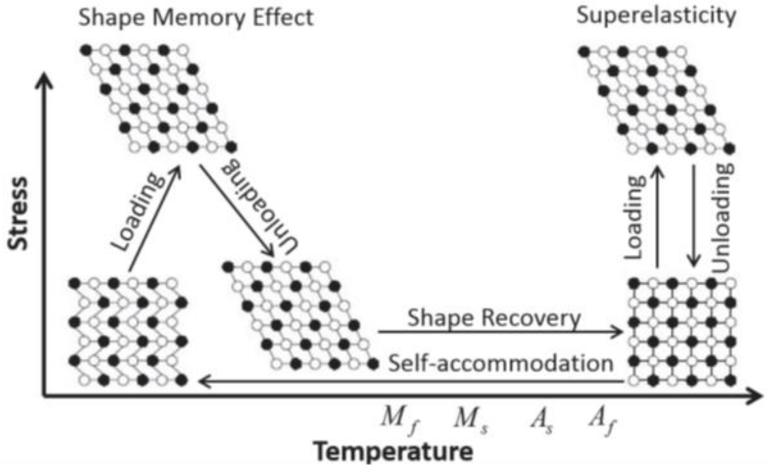


Figure 2.1 : Shape Memory Effects and Superelasticity

Nitinol bars had a nickel to titanium ratio of 0.56:0.44, and were heat treated to produce superelastic response at room temperature. Cyclic tension test was performed by A. Abdulridha et al. (2013) on the 300mm long sample of each reinforcement type. During testing the Nitinol bars were reduced to 9.5mm at mid-height and at the end were threaded and connected to conventional deformed 15M bars with threaded mechanical couples to replicate the system used in the beams. Abdulridha et al. test is about the stress-strain responses of the 10M steel reinforcement and the nitinol bars are as in **Figures 2.2 a) and b**). **Table 1** shows the yield strength, ultimate strength and elastic modulus.

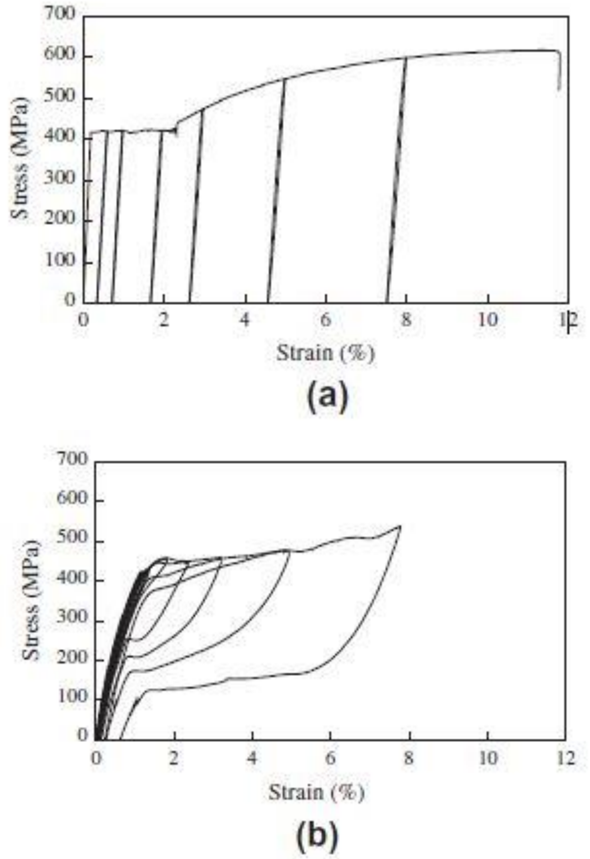


Figure 2.2 : Cyclic stress-strain (a) 10M steel reinforcement; (b) SMA reinforcement

The deformation state from austenite to martensite is supported by DesRoches, Mccormick, & Delemont, (2004). The deformation of SMAs at different stress and temperatures been illustrate in Figure 2.2. DesRoches et al. (2004) in their research investigate the superelastic SMA under cyclic loading to evaluate the use of SMA in seismic application. The cyclic properties of the 1.8mm of SMA wires were compare to 25.4 mm diameter bars to investigate the effect of bar size toward loading history, damping and re-centering properties of SMA. The research resulting ideal properties obtain in wire and bar form for superelastic SMA. However the wire form of SMA shows higher damping properties and strength compare to the bars. The re-centering capabilities based on residual strain were not affected by section size. Above all, the damping properties of SMAs in superelastic form was low for both wires and bars,

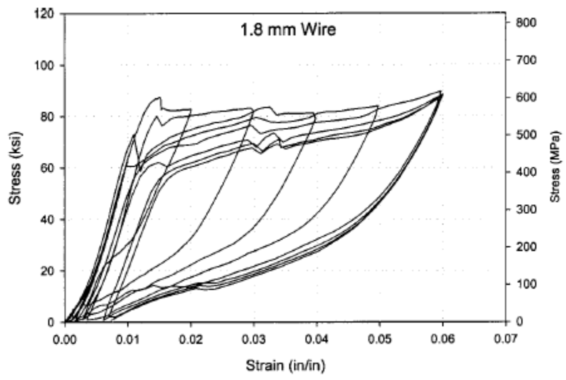


Figure 2.3: Stress-strain diagram for deformation of 1.8 mm diameter Niti SMA wire

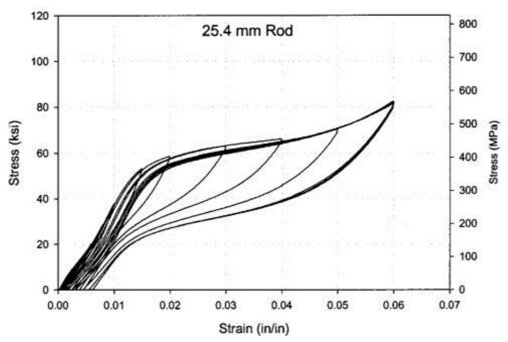


Figure 2.4: Stress-strain diagram for deformation of 25.4 mm diameter Niti SMA bar subjected to Quasi-Static Cyclic Loading (DesRoche et al. 2004)

typically less than 7% equivalent viscous damping. Cyclical strains greater than 6% lead to degradation in the damping and re-centering properties of the SMAs.

The residual strain based on the result provide a clear differentiation between the Nitinol and conventional deformed bars. During the last loading and unloading, the residual strain was 0.65%, representing 91.6% strain recovery. However, the conventional 10M bar residual strain were 7.5% which represent the recovery of 6.25%. This support the objectives of this research because the laboratory result resulting in higher strength and capabilities of the SMA to return to its original forms before stress applied.

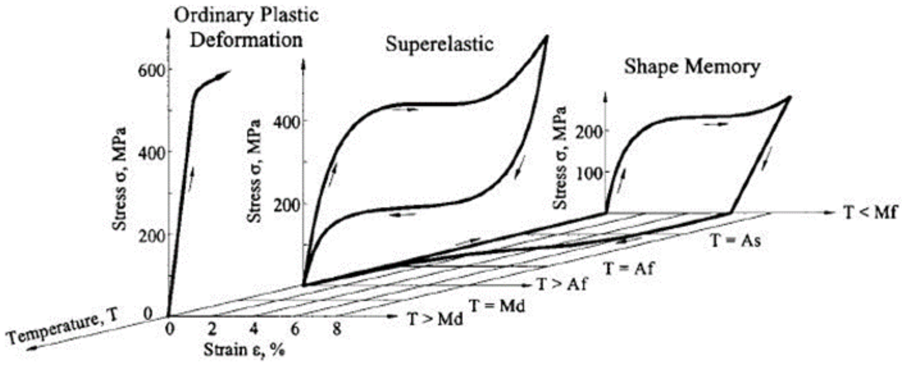


Figure 2.5: Stress-strain diagram for deformation of Niti SMA

Source: DesRoches et al. 2004

2.2 Application of Shape Memory Alloys in modern Structure

SMAs related experimental research in concrete structures has been limited and mostly directed toward new construction. One of the studies are the application of the super elastic SMA bars in precast post tensioned segmental column to non-linear and pseudo-dynamic loading (Nikbakht, Rashid, Hejazi & Osman,2014) other significance studies is performance of Superelastic shape memory alloy reinforced concrete subjected to monotonic and cyclic loading. However, the research in application of Superelastic SMAs and Niti Martensitic SMAs in reinforced concrete structures are still few. Therefore, this research are conducted to analysed the reinforced concrete beam behaviour and performance with SMAs compare to normal reinforcement beam.

Some of the SMA application in seismic performance was related to the application of the Niti Martensitic SMA bars in damping capacity through cyclic analyses which had been done by Moon, Roh, & Cimellaro, (2015). In this study, two types of large Niti SMA bars 36.5mm diameter martensitic bar and 25.4mm superelastic SMA provided as 1% of the cross sectional area of the columns, and different post-tensioning tendon force levels yield which is 30% and 50% of the post tension yield stress. This study resulting in 50% of the post tensioning tendon force slightly increases the lateral resistance capacity of the column while decreases the energy dissipation capacity while the tendon remains elastic.

The application of SMAs in reinforced frame structure nowadays are increasing in numbers due to its effectiveness in seismic related area. The examples of the application is in frame structures, steel frame structures, stay cable bridges, connection of steel structures and simple supported bridges (Figures 4). Due to the increase in acceptance and usage of SMAs in industry the cost for SMAs will greatly impact as it will reduce due to the increment in their application and production.

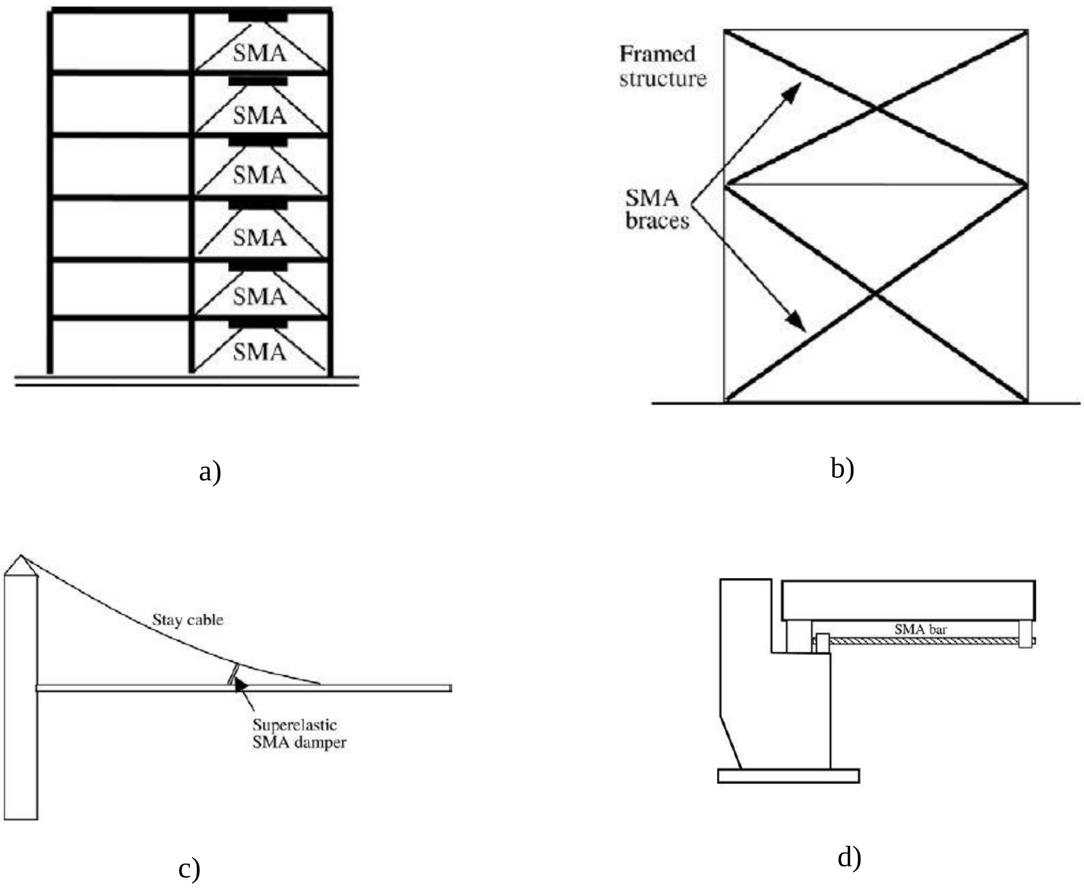


Figure 2.6 :Examples of application of SMAs in Civil structures : a) braced reinforced frame structure; b) braces for two-storey steel frame c) damper for stay-cable bridge e)re strainer for a simple supported bridge

Menna, Auricchio, & Asprone, (2015) in their recent study review of different application in civil stuctures, it has shown how efficient SMA in sensing, enrgy dissipation, actuation, monitoring, vibration control, self-adapting and healing of structures. Furthermore, the succesfull application demonstrated potential for the development of these materials in structural engineering. The key features of SMAs that are exploited for these purposes are the re-centring potential related to superelastic behavior and energy dissipation through hysteretic stress cycles.

2.3 Modelling SMA

Few researcher had proposed uniaxial models for SMA, the superelastic behavior of SMAs had been incorporated in numbers of finite element softwares, ABAQUS, ANSYS and Seismostruct where the materials model had been defined by Aurrichhio and Sacco. (1997). Aurichhio et al. developed the numerical model that closely represent the unusual behavior of the SMA by comparing his numerical simulation result with available experiment data for test being incorporated to test the behavior of SMAs. In their paper, they adopted the classical Euler-Bernoulli Beam theory in modelling single dimensional superelastic SMA elements. The constitutive model developed characterizes the material response in tension and compression as well as the different elastic properties between Austenite and Martensite. Their model takes assumption of full strains recovery and is typical flagged shape response. Linear responses captured the reloading, loading and unloading. The forward and reverse transformation stresses are not in the same in tension and compression, thus resulting in different moment-curvature relationship from that response. The model was proved on four point bending experimental test and four point test on finite element model.

2.4 Niti Martensitic SMA

A lot of studies had been done to increase the energy dissipation capacity of post tension precast segmental column by introducing suitable material for energy dissipation bars. The precast segmental column was most benefited to adapt to the seismic zones and most of the researcher investigate the energy dissipation and other factor for superelastic SMA. This is due to the large inelastic deformation provided by superelastic SMA without significant loss in strength and towards resisting in both tension and compression strength. Moon et al. (2015) in their study investigate the damping capacity of post-tensioned (PT) segmental rocking columns connected with large diameter (36.5 mm) martensitic SMA bars at their base as energy dissipator bars. Apart from that, they also take into consideration of two aspect ratios for the columns:

7.5 for slender and 5.0 for medium size. For an extensive comparison, two various level of post-tensioning force of the tendon are considered. Moment-curvature relationships and complementary computational tools are adopted to model the behavior of (a) lumns. A bilinear model for the PT tendon and a modified four-spring model for the martensitic SMA bar are used. T (b) cast segmental columns are post-tensioned with a tendon in the centerline of the column segments. The post tensioned tendon is left unbonded with the surrounding concrete and provides clamping force required to hold down the column together. This study also use material properties and hysteretic control parameters as tested by McCormick and DesRoches (2004). The cyclic response results show that upon application of 50% post-tension tendon force increase the lateral capacity of the column while decrease the energy dissipation capacity. On the aspect ratio point of view, the column with an aspect ratio of 5.0 activates higher tensile strain behavior of SMA bars and PT tendons; thus resulting in increment of damping ratio even at small lateral displacements. And last but not least the material types, the results show higher equivalent viscous damping ratio when the martensitic SMA bars are used is at 10.5% and 12.5% compare to superelastic bars at about 5% and 7% at almost half of SMA bars.

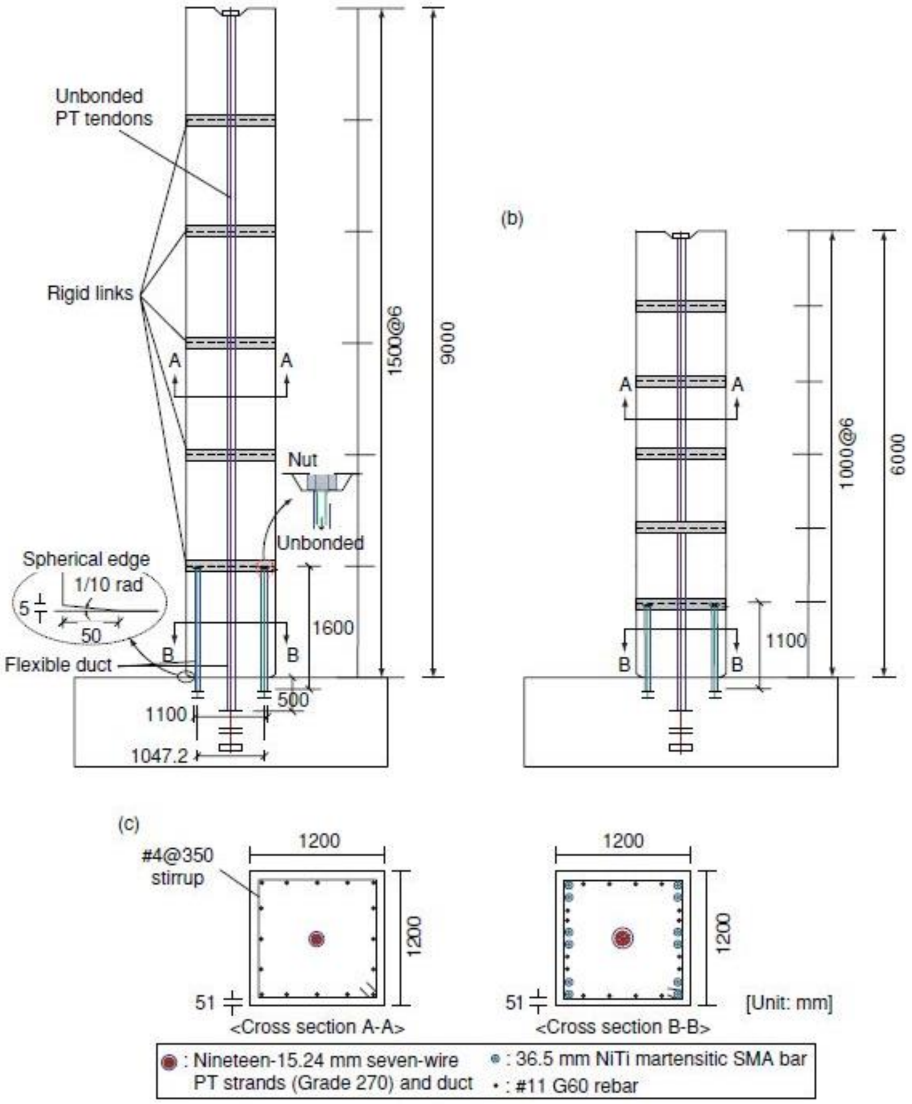


Figure 2.7: Segmental column specimen (a) aspect ratio of 7.5; (b) aspect ratio of 5.0 ; and (c) arrangements of tendon, rebar and SMA bar for sections A-A and B-B

Source: Moon et al. (2015)

Figure show segmental column as tested in Moon et al.(2015) in their study, one of the parameter is the aspect ratio of the column and the purpose is to study the effect of SMA on slender column and medium column. The result show the column with aspect ratio of 5.0 has more higher tensile strain on SMA bars amd PT tendon therefore increasing the damping ratio at small displacement.

CHAPTER 3

METHODOLOGY

In order to achieve desired result as in the objective, proper planning ahead must be take into consideration as time constrain is a major issue towards any projects. The proper experimental method for the numerical modelling of precast post tension segmental column to adapt in numerical modelling.

3.1 Research Methodology

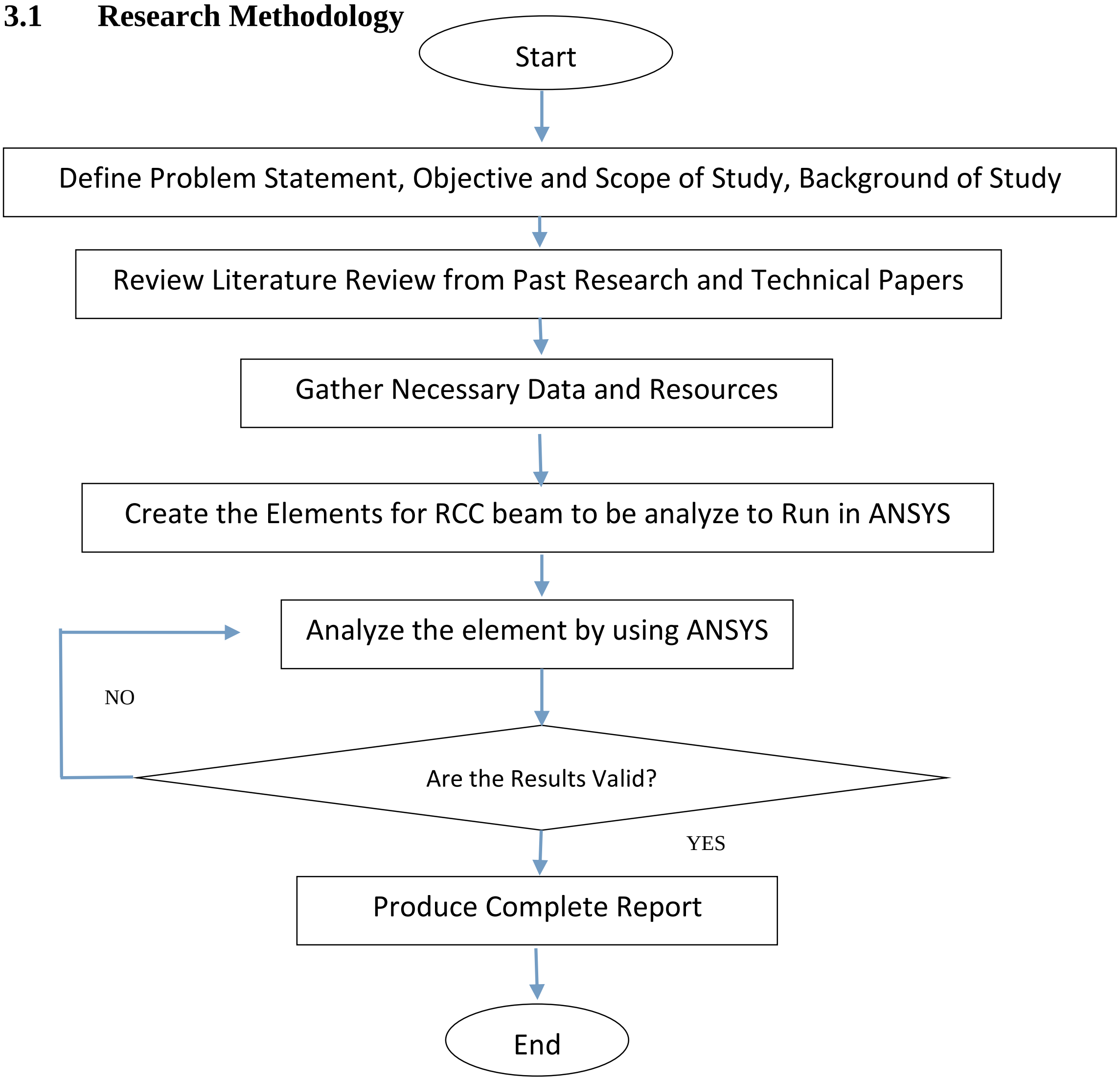


Figure 3.1: Project Flow Chart

3.2 Project Gantt Chart and Key Milestones

FYP I Details of Activities	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Selection of Project Topic														
Preliminary Research Work														
Submission of Extended Proposal														
Presentation of Proposal Defense														
Continuation of Project Work														
Submission of Interim Draft Report														
Submission of Interim Report														

(a)

FYP II Details of Activities	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Continuation of Project Work														
Analyzing result														
Submission of Progress Report														
Continuation of Project Work														
Pre-SEDEX														
Submission of Draft Final Report														
Submission of Dissertation														
Submission of Technical Paper														
Viva														
Submission of Dissertation														

(b)

Key Milestones

Table 3.1: Project Gantt Chart (a) FYP1, (b) FYP2

3.2.1 Project Activities and Key Milestones

This project consists of various stages starting from preliminary studies until the final reporting stage. Each of the activities is important and need to be carry out so that the objectives of the study can be achieved. Nevertheless, the tasks to be performed are within the scope of study and they are specific enough, thus the desired outcomes can be achieved within the specified time frame. Besides, there are some activities or tasks which is critical in this project. These tasks need to be completed on time so that the objectives are achieved and the next tasks can be continued. In essence, these activities are called the project key milestones as summarised in this section.

A) Preliminary Research Work

Further after the topic was finalised, the project was started with few preliminary research works. To begin with, the search was more focus on past research that closely related to this project. Besides that, the most updated available codes and standard for design were also reviewed. The methodology and findings from previous research were noted for report reference. After that, the project problems statements with the objectives and the scope of study are identified. As the problem statement states the common problem faced in the recentness this is our first key milestone. The objective on the other hand will be able to solve the current problem by the end of the study. Furthermore, the scope of study limits the author to a specific area so that the area of study for this project is not too wide and achievable within the specified period of time. More importantly, it conforms to the objectives setting guides which are specific, measurable, attainable, realistic, and within the time frame (S.M.A.R.T.). Then, learning of the finite element software used in this project, specifically ANSYS is necessary as the method of this project.

B) Preliminary Model

As described in the previous section, a preliminary model is produced using a simple column subjected to an axial load on top at the intermediate point. All the keypoint needed for modelling are defined and identified are obtained. In preliminary modelling, the key milestones that can be achieved is to understand and know the basic rules and concept of modelling in ANSYS. For instance, towards the selection of the appropriate material element to simulate the true behaviour of material for shape memory alloy as reinforcement anchor bar as per in real experiment. That is to say, with a simple model this can be easily determined and later can applied directly to the real model. Eventually, it can save a lot of time doing trial and error in the real model which is a time consuming in addition to time taken for analysis to run.

C) Preliminary Results

After the analysis run by the solver, the outputs can be obtained. Basically, the required outputs are such as the segmental column lateral displacement, stresses of concrete, crack and crush and reaction force. Yet, these results need to be validated because it is a computer simulation which might differ from an experiment done in the similar manner. As this effect the result reliability, it consider as one of the key milestone. That said, without a proof to the results, the project may not be continued. Accordingly, the similar model is run in other software the results are compared. However, in this study, the results from ANSYS simulation will be compared against experimental data obtained from previous research.

D) The First segmental column Model

The precast post tension segmental column is modelled to detail as mention. The outputs such as beam displacement and reinforcement strain are extracted from ANSYS. It is then superimposed on the experimental data to see any discrepancies and inaccuracy of the results. The results of the simulation are discussed in the following section.

3.3 Finite Element Method (FEM)

This research project will be done with scope of study to determine the performance difference between conventional normal reinforced concrete segmental column reinforced with two types of Shape Memory Alloy (SMA) which is Superelastic SMA and Niti Martensitic SMA. In this study, the normal concrete mixed design and normal practicable compressive strength will be used for the concrete element. This on the other hand to simulate the effects from the application of SMA for normal building construction. The performance of the mentioned post tensioned segmental column samples are then analyze under lateral and axial loading, and to achieve this ANSYS (2009) is utilized to numerically model the post tension segmental column.

3.3.1 Stress-strain curve of Concrete

Under imposed load, concrete is a quasi-brittle material that has different behavior under compression and tension. Normally, tensile strength of a concrete member is only around 8% to 15% of the concrete compressive strength. A normal stress-strain curve for a normal weight of concrete are shown in Figure 3.3 as developed by **Bangash (1989**).

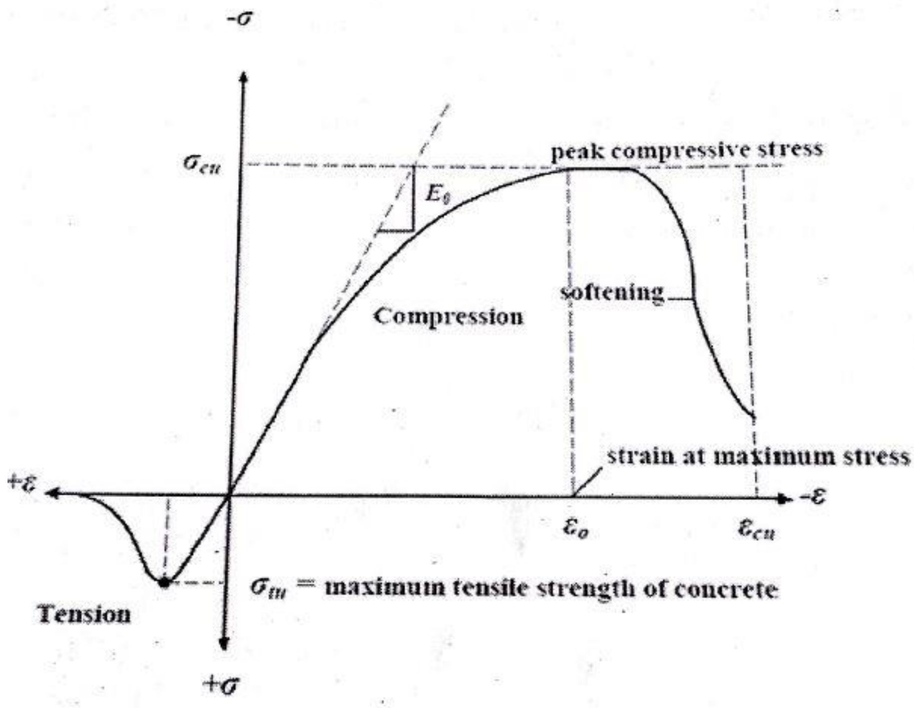


Figure 3.2: Uniaxial compressive and tensile strain curve for concrete

Source: Bangash (1989)

E_o is defined as elasticity of the concrete while σ_{cu} is defined as peak compressive stress. σ_{tu} is defined as maximum tensile strength of concrete. Due to the low tensile strain of the concrete reinforcement was introduced to help overcome the tensile stress.

$$\sigma_{cu} = \left(\frac{E_o}{4700}\right)^2 \tag{1}$$

$$\varepsilon_{tu} = 0.62\sqrt{\sigma_{cu}} \tag{2}$$

σ_{cu} and σ_{cu} are in MPa.

3.3.2 Model of Segmental Column

To simulate the behavior of reinforced concrete segmental column under axial loading, the ANSYS (2013) is used in model and analyzing result. To do this, the utilization of a three-dimensional (3D) finite element program is needed. The analysis result will differentiate the effect of segmental column with both SMAs towards displacement recovery, the strength of column and the crack recovery ability.

3.3.3 Model Description

The sample used in this study are segmental post tensioned column. The top part of the column were steel. The segmental column used consist of 5 segments. The three segment at bottom only the one that has the reinforcement act as anchor inside. The strength of the concrete been used is 40 MPa. All 5 segments were interconnected and held in position by the post tensioned steel tendon that go through the middle of every segment with surface area of 2665mm^2 for the pulling mechanism. The tendon full strength can go up to 1800 MPa. However the tendon was applied only with 0.00041 of strain initially. The reinforcement longitudinal bar which will be using different type of materials were positioned continuously from bottom toe up to 2400mm with 8 total number of bars.

3.3.4 Material Properties

The sample will be model based on previous researcher material properties from their experimental work, this on the other hand help in validating result.

Material	Grade	Elasticity(MPa)	Strength (MPa)
Concrete	40	30241	Fc = 41.4 Ft = 4.053
Prestressed steel	-	200000	Fy = 1800
Mild steel	-	200000	Fy = 410
Column Steelhead	-	200000	-

Table 3.2: Material properties of model

The footing foundation was 1400mm of square and were fixed to the ground. And anchor of 8 bar fully extend from the bottom total of 2413mm from the ground. The top of where the load was applied is a 950 mm square of a steel head with height of 770mm. The steelhead act as the point where most of the forces applied to. The pre-stressing tendon was positioned in the middle for centre through from top to bottom of the segments.

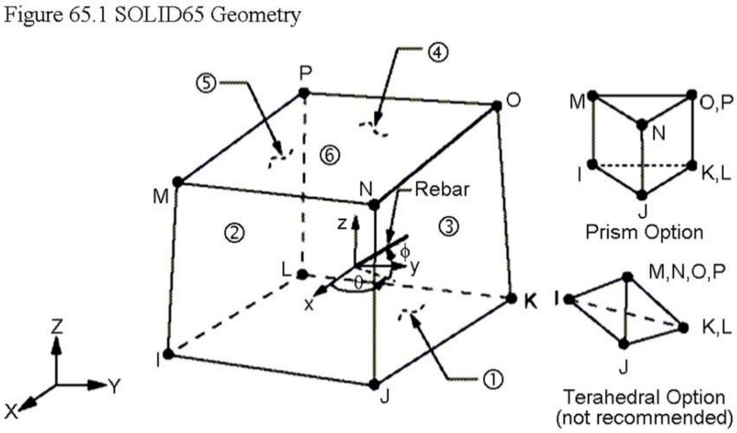
3.3.5 Types of Elements

During the simulation of the elements, it is important to identify the material behavior and the closest element that able to behave and produce results like the actual material. The modelling materials such as the concrete and mild steel reinforcement are selected accordingly to get similar results concerning the stiffness, the yield capacity, the strength energy dissipation and the residual displacement under static loading. The details of the applied element are as followed:

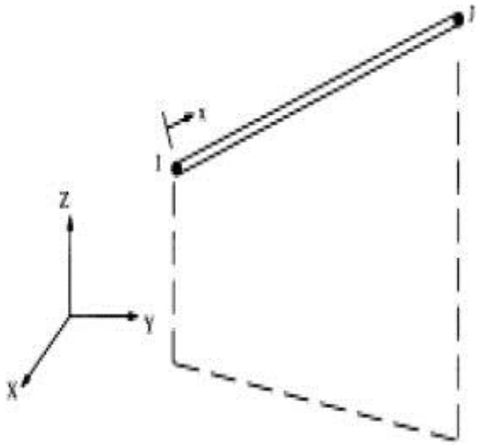
a) Solid65 element is used in modelling the concrete element and defined with 8 nodes and three degree of freedom at each node. The element was capable of showing the cracking, crushing and nonlinear plastic deformation when the concrete is under tension.
b) For the pre-stressing tendon, Link8 element is used to model the pre-stressing tendon and the behavior. However for the latter version of the ANSYS (2009) the Link8 input had been removed but can be retrieved by using commands.

Link8 element has the capability of plasticity, swelling, stress defining and large deflection which is ideal for pre-stressing tendon.

c) During the occurrence of segment uplifts, the stiffness of the contact element between the joints are considered for initial penetration. For this purpose, the Contact174 and Target 170 which implies unilateral flexible surface to surface attributes and the penalty method contact algorithm is selected to model the contact in between the segments. According to ACI the coefficient of friction of 0.5 is used for friction between two adjacent segments.



(a) Solid65



(b) Link8

Figure 3.3 Elements of (a) Solid65 ; (b) Link8 used to represent concrete and mild steel.

3.4 MODELLING OF SUPERELASTIC SHAPE MEMORY ALLOY

The material model of SMA is defined using the Auricchio model (1997) in the finite element analysis of ANSYS package. The idealized stress-strain behavior for this material type is illustrated in Figure 3.5. The constants description are shown in the figure and the values which are applied for the models are shown in Table 3 which apply the SMA properties from Billah and Alam (2012).

For SMA modelling, Solid185 element is used. This element capable of determining the plasticity, stress stiffening, large deflection and large strain.

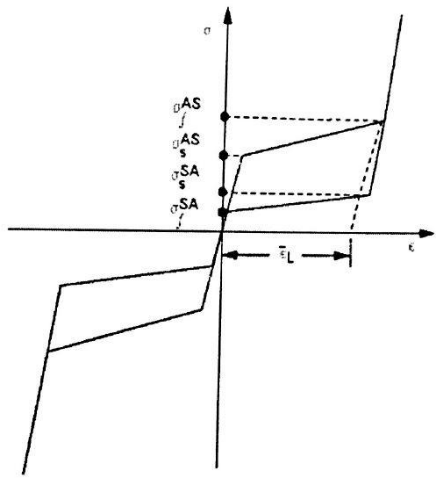


Figure 3.4: Graphical idealization of SMA behavior as defines in Table 3.3

Constants	Description	Value
σ_s^{As}	Starting stress value for austenite phase (MPa)	414
σ_f^{As}	Final stress value for Ustenite phase (MPa)	530
σ_s^{SA}	Starting stress value at unloading stage (MPa)	380
σ_f^{SA}	Final stress value at the unloading stage (MPa)	130
$\bar{e}_L$	Maximum residual strain (%)	6.2
E	Modulus of elasticity(MPa)	54200

Table 3.3 : SMA material properties used for the models

For the modelling of the prestressed segmental column, the material properties will be used in the modelling is as mention before for the segmental column. For both Niti Martensitic and Niti Superelastic SMA bars properties and hysteresis control parameters were as tested by Mc Cormick and Desroches (2004). Each value represents the constants or material behavior of SMA as in Figure 3.5. The first value represents the starting austenite phase or known as the loading phase and at this point the austenite start to yield further to the next value is the final austenite value or final loading point. Next constants indicates starring value for unloading stage or known as the starting martensite phase. Later the final stress unloading stage of the SMA and indicates the final martensite phase. The next constants indicates of maximum residual strain of SMA which is at 6.2% it is the maximum permanent deformation that SMA material. The last constants is E or Young's Modulus of the SMA or the ratio of stress over strain of SMA.

3.4.1 Loading Procedure

Three types of loading procedures are imposed : post-tensioned, axial load and lateral load. The footing is fixed completely during all stages.

a) Post tensioning of pre-stressed strands at centre of column equivalent to 0.00041 of the strain of the strand for the preliminaries value. Post tensioned strand consist of total area of 2665mm. For other post-tensioning value for pre-stress varies for 20%, 40%, 60% and 75% of the total yield strength of the pre-stressed yield stress.

b) Applying axial force of 818 kN at top of the column, representing the weight of concrete equivalent to 0.007fc'Ag. as the model is simulated as symmetry the value were divided into two

c) Lateral loading is applied at the intermidiate point on side of the steelhead at 385mm of height above the column. The lateral displacement applied initially 50mm and increased gradually until column fails.

CHAPTER 4

RESULTS AND DISCUSSION

This section represent the simulation result by the ANSYS on the precast segmental column. The model was simulated based on the methodology and properties discussed in the earlier chapter. The results obtain are validated with the experimental data to access the reliability, accuracy in real experimental situation.

A lot of available ouputs can be obtained from the ANSYS. The main focus here is the performance of the segmental concrete column with different reinforcing material. The performance are evaluated based on the cracks and crushing formation, the gap opening upon load removal, residual deformation of the segmental column and the effect on different post tension stress applied.

4.1 Residual Strain Comparison of 20mm reinforcement bar size

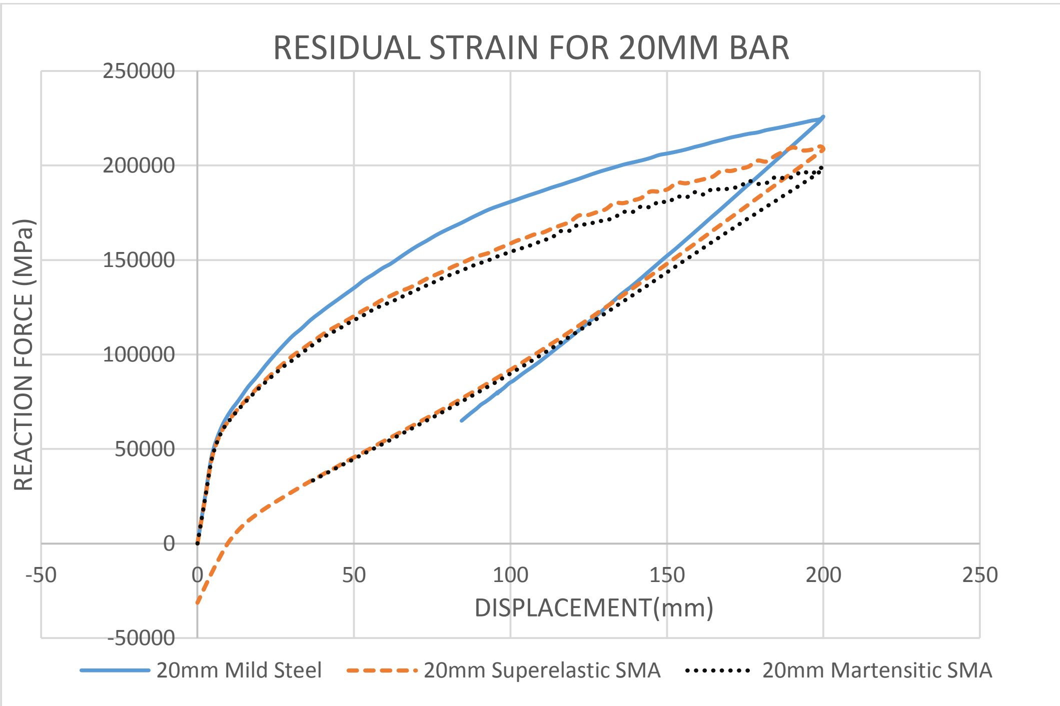


Figure 4.1 Comparison behavior between (a) 20mm diameter mild steel with (b) 20mm diameter Superelastic SMA and (c) 20mm diameter Niti Martensitic SMA

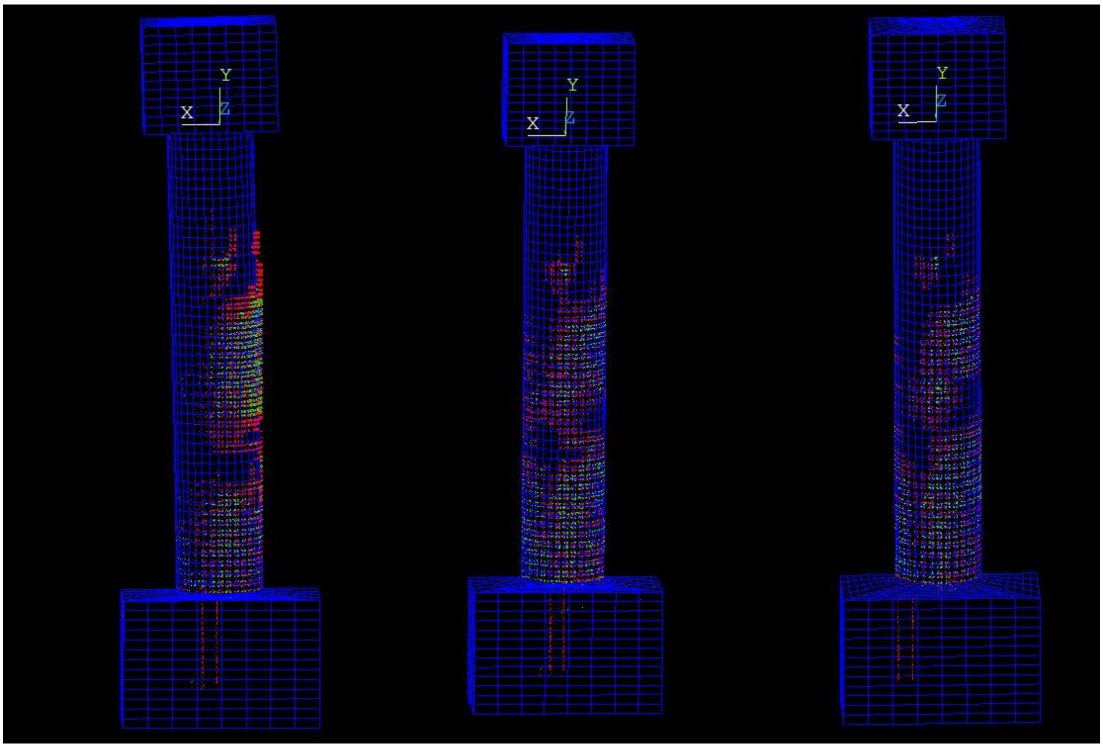
ANSYS finite element solves the strain in each node of an element based on applied displacement. Three model are created towards obtaining the result. The first model are the “20mm MILD STEEL” which been anchored to the bottom of the segmental column with normal industrial reinforcement material or known as mild steel. The second model is “20mm Superelastic Shape Memory Alloy” which is identical to the first model but the anchor reinforcement are modelled as Superelastic SMA. As well as the third model of “20mm Niti Martensitic Shape Memory Alloy” with the reinforcement properties and element of Niti Martensitic SMA.

The model “20mm MILD STEEL” with reinforcement size 20 mm was analyse and the result obtain were as drawn on Figure 4.1. Based on the above result, the impose of the lateral load are from 50mm lateral displacement and gradually increased by 50mm in each run until 200 mm and the lateral load is then released by applying zero displacement to the model. This is subjected to the result obtain from the preliminary run that the model failed at 210mm. The result indicated that mild steel reinforcement with 20mm diameter bar peak at around 225MPa reaction force. However as the similar loading procedure been applied to the model with SMA as the reinforcement bar the results show the model with Superelastic SMA has lower reaction force at 208 MPa; as well as the model with Niti Martensitic SMA with 200MPa. The difference of 17MPa of the model with mild steel and superelastic SMA indicates the higher strength of the mild steel compare to the SMAs. The primary reason for this high value of reaction force in the first model is due to its higher ductility effect than SMA to compare with. For instance, the Modulus of elasticity used in the modelling of the normal reinforcement bar is highest at 200000MPa compare to SMA with only 64200 MPa and 38000MPa for martensitic SMA.

Upon released of the lateral push displacement the results shows all three model are returning to the original position. However, the result from “20mm MILD STEEL” indicated that the model was unable to return to its original position and stops at 83mm of displacement. Compare to the other SMA model which returned to 9mm from total of 200mm. And for the Niti Martensitic the result stops at 35mm. The returning result indicates the returning rate of the column with superelastic SMA are more favourable towards residual strain at 200mm deflection and more than 200kN of lateral force resisted. The model with the mild steel reinforcement halt at 83mm is because of the concrete failure due to excessive stress to deflect the mild steel anchor reinforcement. On the other hand, for the model with Niti Martensitic reinforcement anchor the concrete fail due to the martensitic bar yield up to its maximum limit and fail. The residual strain for the first model was at 41.5%. For the superelastic SMA the result for the 20mm bar size model shows that the strain was at 5% and model with Martensitic SMA at 18%.

4.1.1. Crack and crush comparison

One of the available output was to show the crack and crush form at the column. Figure 4.2 below show the crack and crush distribution pattern at their final residual deflection.



(a) (b) (c)

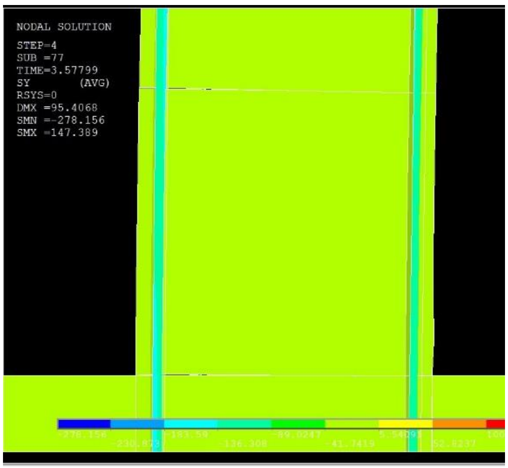
Figure 4.2 : Back view crack and crush formation on segmental column at (a) 20mm MILD STEEL (b) 20mm Superelastic Shape Memory Alloy (c) 20mm Niti Martensitic Shape Memory Alloy

During meshing work, the determination of the mesh size is important to help show crack pattern. As mention before the mesh size used is suitable for this modelling which is at 75mm as the bigger the size the result will be less accurate. But for smaller meshing size the analysis will require much longer time to analyze the element. From the result, if we observed from the bottom of the column steelhead to the bottom; the precast segmental concrete column (a) the 2nd and 3rd segment shows large crack formation and at higher intensity at the right side of the picture or the right side of the column. In comparison to both SMA model which show low crack form and less crack intensity. The difference in crack pattern are the results to the higher stiffness of the mild steel reinforcement and induced more stress to deform the bar thus creating more crack when the steel yielding.

In contrast to the mild steel the less crack pattern formed on the Niti Martensitic SMA as it is way more elastic than the other material compared to. The crack formation is important as it limitation in our design standard and specification. With the implementation of SMA in reinforcement to help act as a hybrid reinforcement at the bottom anchor footing the limit can be increased. However, future works are recommended in determining suitable limit to optimize the SMA usage in anchor work. Furthermore, if the formation of crack are less tit will benefit the authorities and public as it will reduce time and cost to repair.

Moving down to the lower segment the fourth and the fifth segments, the crack formation show higher intensity and area with crack. This is due to the shear crack at the inelastic region of the pier.

4.1.2. Gap and opening



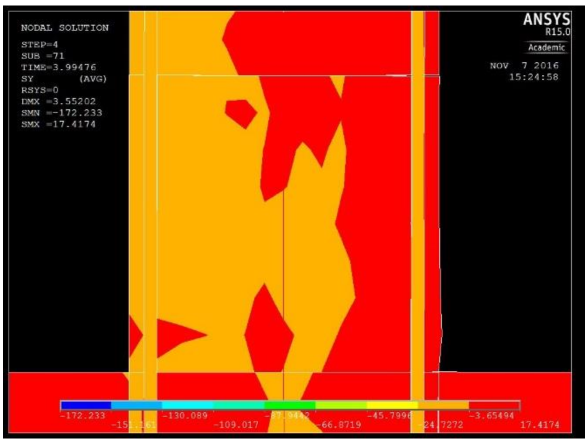


Figure 4.3 : Close up view stress contour and gap on segmental column at left 20mm MILD STEEL and right Superelastic SMA model.

The gap and opening in between each segment show after returning position. The result show smaller gap on segment with Superelastic SMA bar. For seismic structures gap closing are beneficial to the structure to prevent from corrosion and to protect the reinforcement. As the Superelastic SMA has more elasticity it helps in closing gap even after undergoing large deflection.

4.2 Effect of different Post-tensioned stress on precast segmental column

In precast segmental column, the post tensioned are used mainly to connect all segment together by going through the middle of every segment and locked with percentage of the tensile stress. It also helps in self centering effect of the precast segmental column as it deflect laterally. Previous researchers found that the effect of different post-tension stress applied is significance in self centering effect and help close gap and opening induced. As the opening in concrete is not favorable and lead to corrosion effect this self-centering are great invention towards resisting lateral deflection for instance the earthquake. Towards the application of this new material of SMA in the precast segmental column, the performance of the column need to be identified to choose the optimum value to help in self-centering effect.

4.2.1 Model with 20% of post-tensioned stress

The post tension strand use in this model has a yield stress of 1800 MPa. To apply 20% of its yield stress is by using stress strain equation.

$$\sigma = 20\% \times 1800MPa = 360MPa \tag{3}$$

, δ is then divided by the modulus of elasticity of the prestress tendon

$$\varepsilon = \frac{\sigma}{E} \tag{4}$$

as the value to input in ANSYS in post tension is in strain the value input are 0.0018. the analysis run produce result as in Figure 4.3 below.

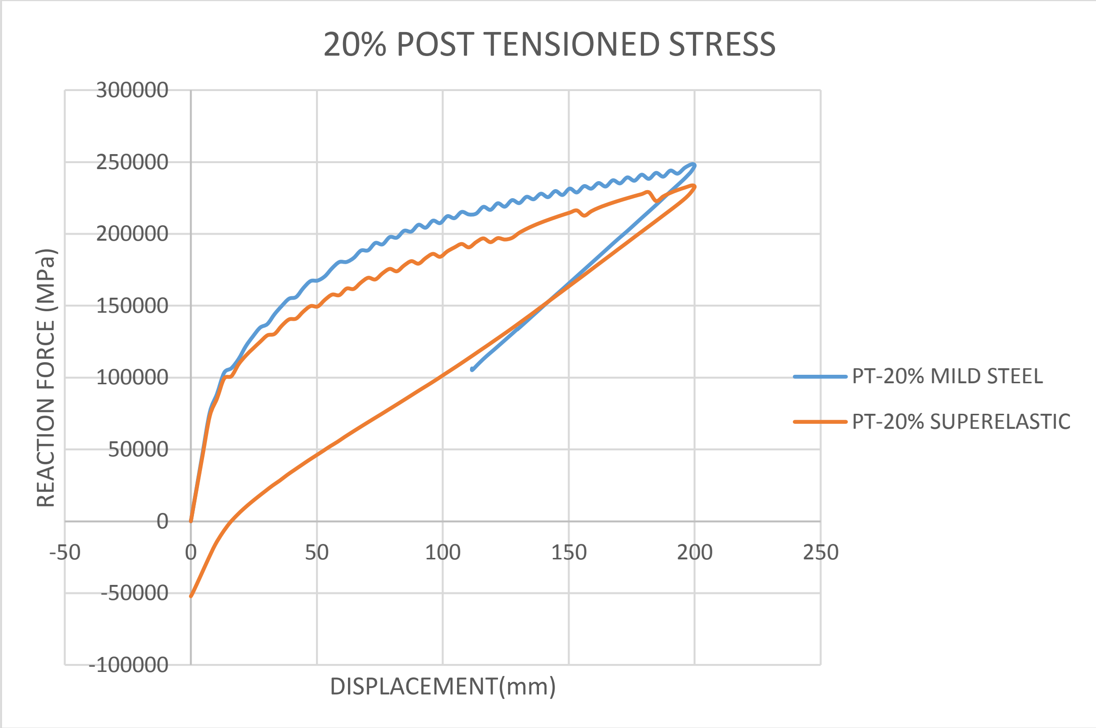


Figure 4.4:Figure show the graphical representation of the mild steel and superelastic SMA with 20% post-tension stress.

From the result shown on graph, both model show steep increment of reaction force from applied deflection from 0 to 85 mm deflection both model can reach 100MPa at both linear behavior. Further increment the value start to increase at higher stress for mild steel and followed by the superelastic SMA. Both model start to yield at almost the same displacement. Further application of the lateral load increased the stress gradually up to 200 mm at 247 MPa for mild steel reinforced model and 232 MPa for Superelastic SMA model. Upon removal of lateral deflection, the 20% post tension stress still cannot help in self centering of the precast segmental column as the mild steel still cannot return to 0 displacement upon removal of load. However in the SMA model the residual deformation increased to 15mm with the increment of post tension. The increment of the post tension strain thus increased the lateral resistance of the column. Therefore, the post tension strain value need further increment.

4.2.2 Model with 40% of post-tensioned stress

As Calculated using equation (4) and (3) the strain value for the post tension is 0.0036. The model was analysed for 40% of the post tension strand yield stress. The result was as shown below in the figure.

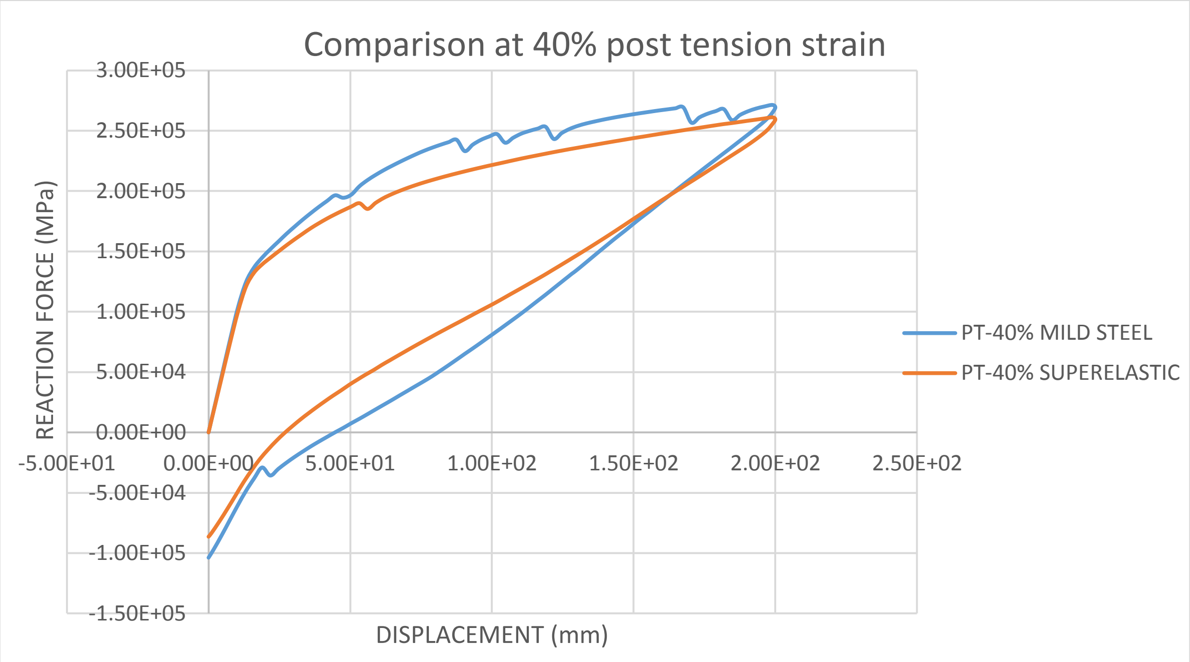


Figure 4.5: Graph of post tension effect for model with 40% of post tension strand yield stress.

Based on the result, both model react linearly up to their yield start point of 120 MPa at 13mm. Further load increment diverse both model. The model with mild steel at 200mm reaction lateral deflection is up to 269 MPa. Slightly lower at 260MPa for SMA model for 200 mm displacement. Upon load removal, the mild steel has self-centering effect and have permanent displacement at 44 mm. However, for the model with SMA the permanent displacement was at 27 mm. This result show that the increment in post tension strain increased the lateral deflection value but also increased the self-centering effect.

4.2.3. The model with 60% of post-tensioned stress

Based on previous subsection, the model of 40% of yield prestressed still cannot reduce the permanent deformation of the precast segmental column. The value calculated to input as strain at post tension in modelling is 0.0054 from the equation (3 and 4). The analysed result are as shown in figure below.

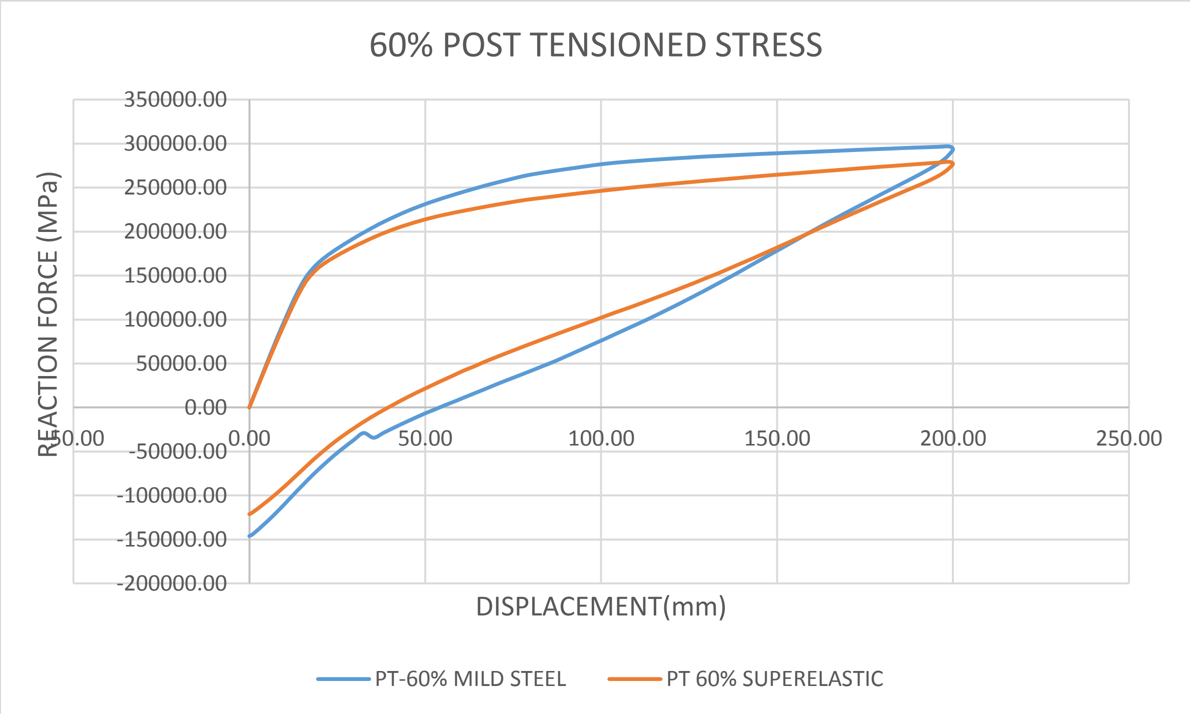


Figure 4.6: Graph of post tension effect for model with 60% of prestressed strand yield stress.

Based on the result shows that both the model inititially increase linearly up to 18mm of deflection with 150 MPa of lateral force. Further load increment divide the model as it start to yield.the model with mild steel yield up to 300MPa at 200 mm of displacement. Compare to model with SMA the model yield until 276MPa at 200mm displacement. Upon the removal of lateral load both model return to the original position. The permanent displacement for model with mild steel is at 55mm and model with SMA reinforcement is at 40mm. Thus shows that the effect of post-tension on self-centering had increased but the permanent deformation is still larger. This may be due to some modelling error which will be discussed later.

4.2.4. The model with 75% of post-tensioned stress

As predecessor from the previous result, the strain input are calculated using similar equation (3) and (4) as previous subsections. The input value is 0.00675 for the strain of the post tension tendon. The model are analysed and the result obtain were as shown in Figure 4.6 below.

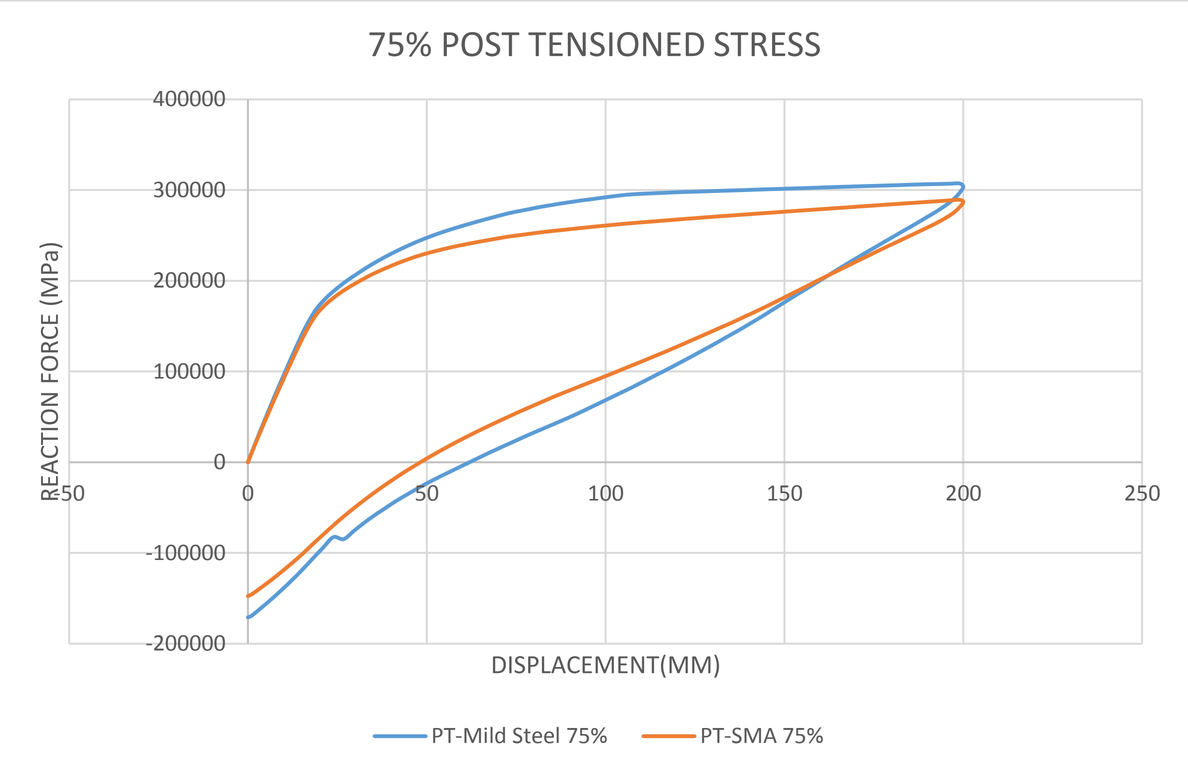


Figure 4.7: Figure above represent the effect for model with 75% of post tension strand yield stress.

Result show the model behavior when the post tension applied stress was at 75% from the post tension strand yield stress. Both model increase at similar linear rate up to the yield start point at start to diversify in the reaction and mild steel as expected create large gap of difference as both model approaching 200 mm of displacement. As the deflection increase gradually the lateral force induced in model with mild steel show small and constant steady increment from 130mm up to the maximum deflection. The reaction force at maximum lateral displacement for the model with mild steel achieve 303MPa compare to SMA at 286MPa of lateral force. Upon load removal, the model with mild steel decrease at nearly linear and the permanent displacement is at 61 mm for mild steel model and 49mm for SMA model. Above all, the effect of increasing post tension strain is it can increase the lateral resistance of the precast segmental column however, the self-centering effect is still not as expected to be. Despite this, the increment in post-tension stress also increase the permanent displacement of the precast segmental column. This may be in occurrence of the faulty modelling phase, because the crucial part of this model is to model the longitudinal bar of reinforcement and the contact behavior in between the reinforcement bar with the concrete segment.

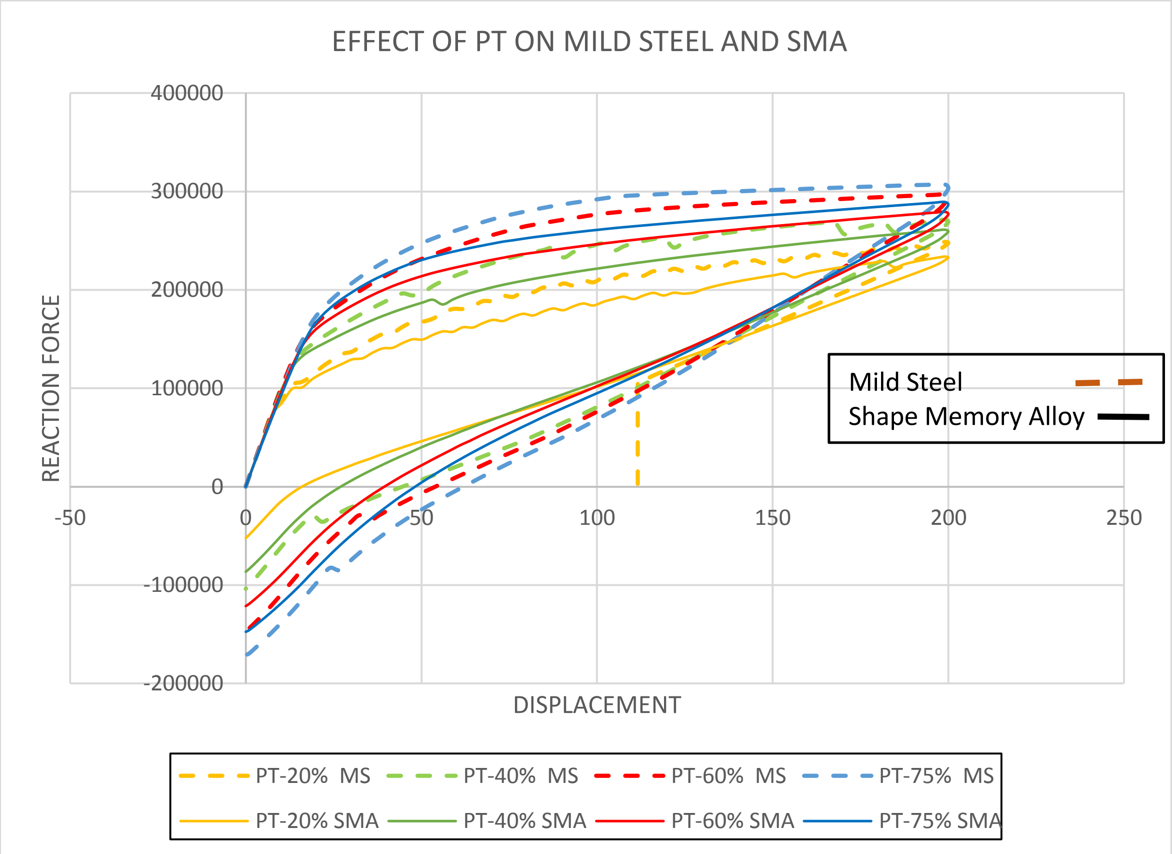


Figure 4.8: Both model at different post tension strain.

Figure show the comparison on the stress induced by increasing the post tension stress in the model and the effect on the permanent deformation. This shows both 75% and 60% of applied post tension on mild steel model had the large lateral resistance compare to other model. However the permanent displacement is also large due to yielding of the material.

CHAPTER 5

CONCLUSION

Based on discussion on previous sections, few conclusion can be made up. Reinforcement material is important in reinforced concrete structure as it help in preventing crack during shrinkage and help in resisting tensional force. This paper investigates the performance of shape memory alloy as longitudinal reinforcement at inelastic region in precast segmental column. As a comparison, normal mild steel is used also in same loading procedure and the result is compared to. On the other hand, another type of shape memory alloy which is Niti Martensitic is also used to compare the performance towards lateral deflection. Superelastic shape memory alloy show high stress value and at the same time ability to undergo small permanent deformation even though the material undergo large strain deformation to compare with other materials. All three model cracks formation behavior show different behavior. The less crack formation Niti martensitic SMA model due to the elasticity of the material. Besides that, the effect of applying higher post-tensioning tendon to the precast segmental column slightly increase the lateral resistance capacity while reducing the effectiveness in permanent deformation. However, increment in post tensioning force help increase the mild steel effectiveness in permanent deformation and re-centering capability of the column but it is only slightly effective not so significant impact. Therefore, the material selection types of SMA bars is the most effective to enhance the seismic performance based on its ability to take high load and still does not effect the ability to have small residual displacement. On the other hand, the post tensioning force have small impacts on residual strain of the material tested. Therefore it is concluded that the use of Superelastic SMA in precast post tension segmental column is more preferable compare to other type of bar to help reduce the residual displacement of the column and increase the energy dissipation capacity of the column. For future work, it is recommended to include the size and number of segmental column in analyzing the self-centring effect.

REFERENCES

Abdulridha, A., Palermo, D., Foo, S., & Vecchio, F. J. (2013). Behavior and modeling of superelastic shape memory alloy reinforced concrete beams. Engineering Structures, 49, 893-904. doi: 10.1016/j.engstruct.2012.12.041

Auricchio, F., Taylor, R. L., & Lubliner, J. (1997). Shape-memory alloys: macromodelling and numerical simulations of the superelastic behavior. *Computer methods in applied mechanics and engineering, 146*(3), 281-312.

ANSYS (2009), User's manual, Theory reference for the mechanical APDL and mechanical applications.

Bangash, M. (1989). Concrete and concrete structures: Numerical modelling and applications.

DesRoches, R., McCormick, J., & Delemont, M. (2004). Cyclic properties of superelastic shape memory alloy wires and bars. *Journal of Structural Engineering*, *130*(1), 38-46.

Menna, C., Auricchio, F., & Asprone, D. (2015). Applications of Shape Memory Alloys in Structural Engineering. *Shape Memory Alloy Engineering,* 369-403. doi:10.1016/b978-0-08-099920-3.00013-9

Muntasir Billah, A. H. M., & Shahria Alam, M. (2012). Seismic performance of concrete columns reinforced with hybrid shape memory alloy (SMA) and fiber reinforced polymer (FRP) bars. *Construction and Building Materials, 28*(1), 730-742. doi: http://dx.doi.org/10.1016/j.conbuildmat.2011.10.020

Moon, D., Roh, H., & Cimellaro, G. (2015). Seismic Performance of Segmental Rocking Columns Connected with NiTi Martensitic SMA Bars. *Advances in Structural Engineering, 18*(4), 571-584. doi:10.1260/1369-4332.18.4.571

Nikbakht, E., Rashid, K., Hejazi, F., & Osman, S. A. (2014). Application of shape memory alloy bars in self-centring precast segmental columns as seismic resistance. *Structure and Infrastructure Engineering, 11*(3), 297-309. doi:10.1080/15732479.2013.876056

Song, G., Ma, N., & Li, H.-N. (2006). Applications of shape memory alloys in civil structures. *Engineering Structures, 28*(9), 1266-1274.

Appendixes

Appendix 1

1) Concrete stress strain determination:
2) Maximum tensile stress of concrete $= 0.63\sqrt{\sigma cu}$

$= 3.98$

3) $E_c = 4700\sqrt{fc'}$, use 41.4 for concrete strength

$= 4700\sqrt{41.4}$

$= 30241$

4) $\varepsilon^{\circ} = \frac{2fc\prime}{Ec}$, strain at peak

$$\varepsilon^{\circ} = \frac{2(41.4)}{30241}$$

$$\varepsilon^{\circ} = 0.002738$$

5) $fc = \frac{Ec\ \varepsilon}{1+\frac{\varepsilon}{\varepsilon^{\circ}}^{2}}$, compressive stress

$$fc = \frac{30241(0.0005)}{1+\frac{0.0005}{0.002738}^{2}}$$

$$fc = 15.1205$$

6) Step 5 repeated for 5 points at different ε

Stress	Strain
15.1205	0.0005
26.68	0.001
30.44	0.0012
34.89	0.0015
39.44	0.002
41.4	0.00269

Appendix 2

Axial load

$$= 0.007 \times fc' \times Ag$$

$$Ag = \frac{\pi d^2}{4}$$

$$Ag = \frac{\pi 610^2}{4}$$

$$Ag = 292246$$

$$= 0.007 \times 41.4 \times 292246$$

$$= 818290$$

Divide by 2 as the model is symmetry.

And divedi by 2 again for the axial load is applied at 2 point.

Axial load = 204572 in –y direction

Appendix 3

Post tension strand

$$\delta = 20\% \times 1800MPa = 360MPa$$

$$\varepsilon = \frac{\delta}{E} = 0$$

$$\varepsilon = \frac{360MPa}{200000MPa} = 0.0018 \tag{5}$$

Percentage of post tension	Strain value
20%	0.00180
40%	0.0036
60%	0.0054
75%	0.00675

Strain value is input in command for both model.

Appendix 4

Table for graph of result obtain in mild steel model.

mild steel

TIME	displacement	force	2.41	81.81	167694.33
0.20	0.00	0.00	2.42	84.67	169907.01
0.40	0.00	0.00	2.44	87.52	172345.33
0.70	0.00	0.00	2.45	90.38	174613.35
1.00	0.00	0.00	2.47	93.24	176783.81
1.08	0.00	0.00	2.48	96.10	178535.92
1.17	0.00	0.00	2.49	98.95	180194.28
1.29	0.00	0.00	2.51	101.81	181835.56
1.48	0.00	0.00	2.52	104.67	183531.31
1.68	0.00	0.00	2.54	107.52	185097.29
1.88	0.00	0.00	2.55	110.38	186672.45
2.00	0.00	0.00	2.57	113.24	188353.46
2.01	1.33	13585.18	2.58	116.10	189794.49
2.01	2.67	27155.72	2.59	118.95	191377.23
2.02	4.67	47142.73	2.61	121.81	192915.46
2.04	7.52	61011.47	2.62	124.67	194598.79
2.05	10.38	69609.19	2.64	127.52	196214.49
2.07	13.24	75976.24	2.65	130.38	197675.27
2.08	16.10	82712.52	2.67	133.24	199024.21
2.09	18.95	88269.13	2.68	136.10	200445.99
2.11	21.81	94308.61	2.69	138.95	201564.07
2.12	24.67	99784.71	2.71	141.81	202660.77
2.14	27.52	104968.94	2.72	144.67	203942.73
2.15	30.38	109807.81	2.74	147.52	205548.08
2.17	33.24	113769.85	2.75	150.38	206416.17
2.18	36.10	118210.84	2.77	153.24	207381.51
2.19	38.95	121878.49	2.78	156.10	208484.61
2.21	41.81	125477.58	2.79	158.95	209821.22
2.22	44.67	128851.02	2.81	161.81	210963.07
2.24	47.52	132285.39	2.82	164.67	212354.12
2.25	50.38	135650.90	2.84	167.52	213508.62
2.27	53.24	139371.71	2.85	170.38	214767.41
2.28	56.10	142315.34	2.87	173.24	215745.61
2.29	58.95	145513.36	2.88	176.10	216758.87
2.31	61.81	148113.80	2.89	178.95	217472.73
2.32	64.67	151368.06	2.91	181.81	218727.47
2.34	67.52	154581.03	2.92	184.67	219621.10
2.35	70.38	157563.84	2.94	187.52	220570.42
2.37	73.24	160164.65	2.95	190.38	221586.96
2.38	76.10	163002.52	2.97	193.24	222580.33
2.39	78.95	165453.12	2.98	196.10	223656.46

2.99	198.95	224506.55
3.00	200.00	225877.81
3.01	198.67	223221.45
3.01	197.33	221186.46
3.02	195.33	218211.03
3.04	192.48	213965.60
3.05	189.62	209731.99
3.07	186.76	205513.18
3.08	183.90	201320.30
3.09	181.05	197112.00
3.11	178.19	192909.51
3.12	175.33	188920.65
3.14	172.48	184671.28
3.15	169.62	180446.15
3.17	166.76	176246.62
3.18	163.90	172155.34
3.19	161.05	167937.00
3.21	158.19	163772.64
3.22	155.33	159639.20
3.24	152.48	155493.64
3.25	149.62	151650.48
3.27	146.76	147561.53
3.28	143.90	143462.60
3.29	141.05	139366.92
3.31	138.19	135430.81
3.32	135.33	131783.69
3.34	132.48	127635.09
3.35	129.62	123579.11
3.37	126.76	119579.08
3.38	123.90	115608.23
3.39	121.05	111679.64
3.41	118.19	107791.81
3.42	115.33	104088.36
3.44	112.48	100350.01
3.45	109.62	96625.70
3.47	106.76	93154.21
3.48	103.90	89901.79
3.49	101.05	86268.77
3.50	99.62	84873.93
3.51	98.19	82721.56
3.51	97.12	81323.03
3.52	96.58	80599.92
3.52	96.58	80643.39
3.52	96.58	80607.69
3.52	96.58	80606.98
3.52	96.57	80600.22
3.52	96.57	80590.05
3.52	96.55	80576.24
3.52	96.54	80563.19
3.52	96.53	80538.99
3.52	96.51	80727.47
3.52	96.47	80683.24
3.52	96.42	80615.05
3.52	96.34	80514.69
3.52	96.23	80368.78
3.52	96.06	79782.43
3.52	95.80	79370.39
3.52	95.79	79957.18
3.52	95.79	79859.25
3.52	95.79	79942.48
3.52	95.79	79946.61
3.52	95.78	79710.43
3.52	95.77	79805.41
3.52	95.75	79795.20
3.52	95.73	79767.70
3.52	95.70	79722.98
3.52	95.64	79651.04
3.52	95.57	79557.89
3.52	95.45	79407.44
3.52	95.28	79177.02
3.52	95.02	78839.82
3.53	94.63	78326.12
3.53	94.05	77544.67
3.53	93.17	76387.46
3.54	91.86	74817.64
3.55	90.54	73432.11
3.55	89.23	71464.48
3.56	87.26	68927.58
3.58	84.40	64954.94

Appendix 5

Material properties used in modeling.

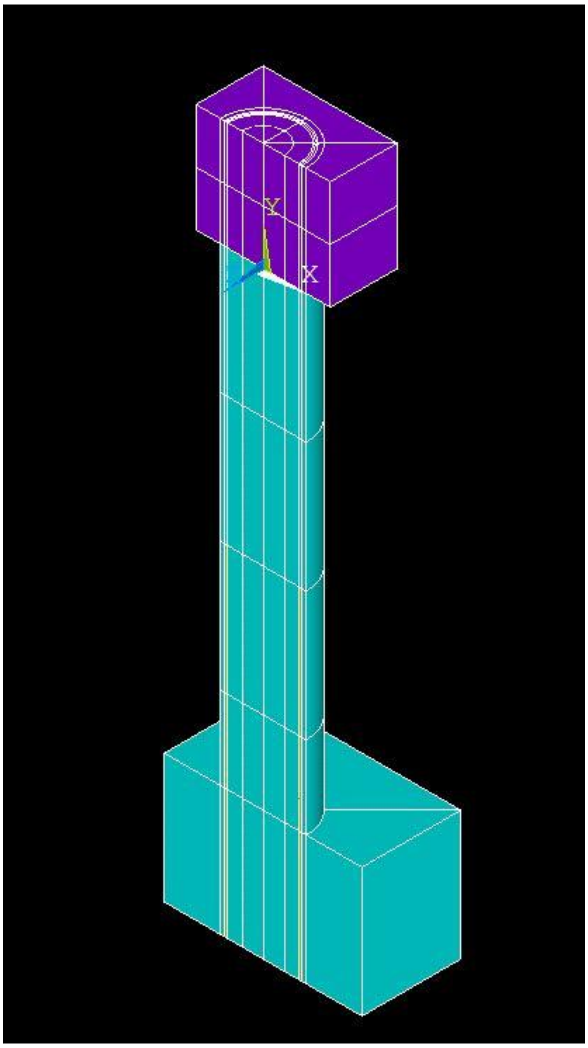
Concrete	Compressive stress, $f_c^{'}$	40 MPa
	Elastic modulus, E_c	31.5 GPa
	Yield strain, ε_{cy}	0.0013
	Nominal strain, ε_0	0.002
	Ultimate strain, ε_u	0.006
Reinforcement	Yield stress, f_y	413.7 MPa (G60)
	Elastic modulus, E_s	200 GPa
Tendon	Elastic modulus, E_T	196.5 GPa
	Yield stress, $f_{y,T}$	1690 MPa (G270)

	36.5mm diameter NiTi martensitic SMA bars	25.4mm diameter NiTi superelastic SMA bars
E_0	38GPa	28GPa
σ_y^+	180MPa	380MPa
σ_y^-	-280MPa	-
α_1	0.118	0.076
α_2	-	0.25
ε_y^+	0.0047	0.0139
ε_y^-	-0.0068	-
ε_{gap}	0.055	0.04
ε_m	-	0.06

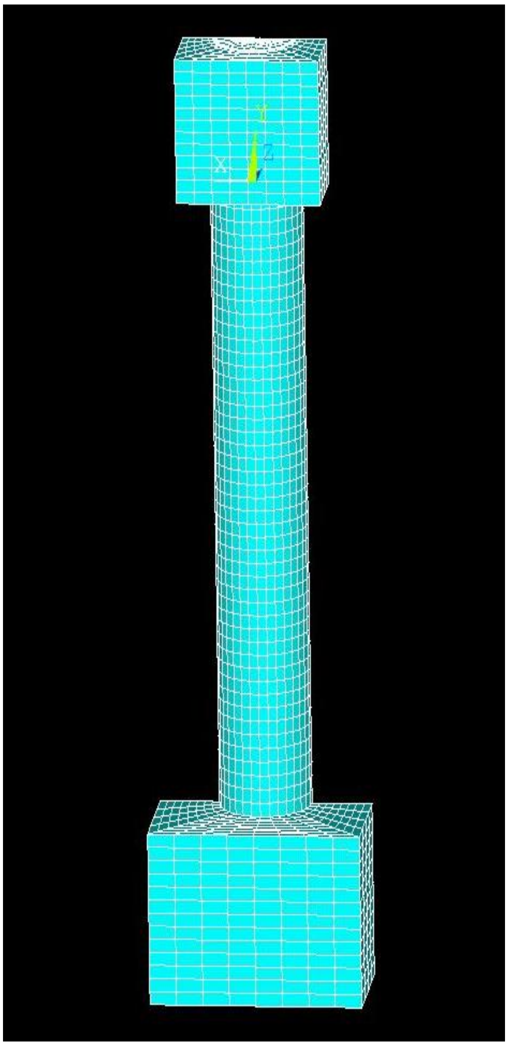
Shape memory alloy properties as done by DesRoches et al. (2004**)**

Appendix 6

Model simulated

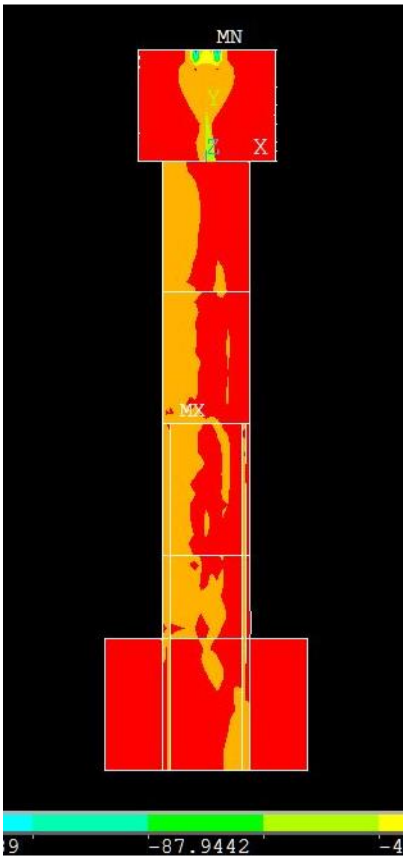


(a)

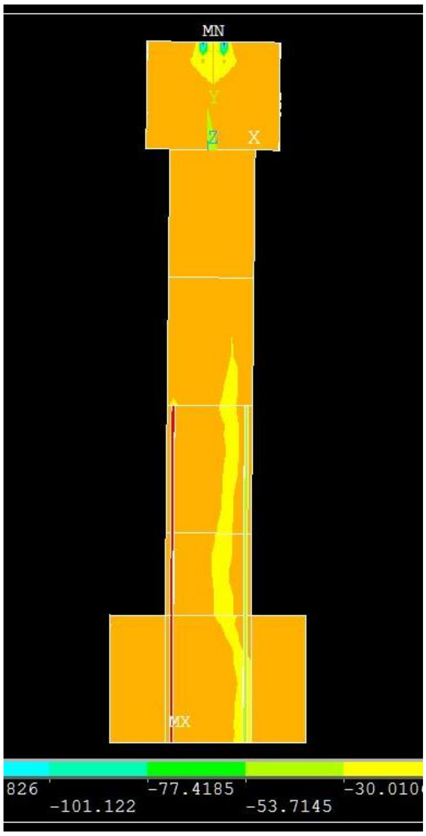


(b)

Precast segmental column as simulated in ANSYS. The (a) show the volume and different element type. Reinforcement bar can be seen from bottom of footing up to third segment. The top is the steel column head for lateral load application. (b) on right show simulated model meshed to 75mm from back view.



Stress contour on superelastic SMA



Stress contour on martensite sma