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COMPARATIVE STUDY OF STEEL AND AFRP TENDONS WITH OPTIMIZED PRE-STRESSING FORCE FOR SCPC JOINTS

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by

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CANDIDATE'S DECLARATION

I **SAJIL A** (2K22/STE/14) hereby certify that the work which is being presented in the thesis entitled "**Comparative study of steel and AFRP tendons with optimized pre-stressing force for SCPC joints**" in partial fulfillment of the requirements for the award of the Degree of **Master of Technology**, submitted in the Department of Civil Engineering, Delhi Technological University is an authentic record of my own work carried out during the period from August 2023 to May 2024 under supervision of **Dr. Nirendra Dev, Professor, DTU**

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other institute.

Sajil A

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This is to certify that the student has incorporated all the corrections suggested by the examiners in the thesis and the statement made by the candidate is correct to the best of our knowledge.

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Certified that **SAJIL A** (2K22/STE/14) has carried out their research work presented in this thesis entitled **“Comparative study of steel and AFRP tendons with optimized pre-stressing force for SCPC joints”** for the award of **Master of Technology** from the Department of Civil Engineering, Delhi Technological University, Delhi, under my supervision. The thesis embodies results of original work, and studies are carried out by the student himself and the contents of the thesis do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University/ Institution.

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ABSTRACT

This thesis presents a comprehensive investigation into the seismic performance of Self-Centering Prestressed Concrete (SCPC) joints reinforced with steel tendons and the innovative Aramid Fiber Reinforced Polymer (AFRP) tendons under cyclic loading conditions. The primary objective is to evaluate and optimize the structural behaviour of these joints to enhance their seismic resilience and facilitate rapid post-earthquake recovery.

Extensive numerical simulations were conducted using the advanced finite element software Abaqus, enabling a detailed comparison of the load-displacement response, energy dissipation capabilities, and residual deformations of SCPC joints reinforced with steel tendons and AFRP tendons, respectively. The results revealed distinct behavioural differences between the two tendon materials.

SCPC joints with steel tendons exhibited high initial stiffness due to the inherent properties of steel. However, upon reaching yield, the steel tendons underwent plastic deformation, contributing significantly to energy dissipation but leaving the joints susceptible to permanent residual displacements after unloading. This residual deformation can necessitate extensive post-earthquake repairs, hindering rapid recovery efforts.

In contrast, SCPC joints reinforced with AFRP tendons demonstrated comparable initial stiffness to steel tendon joints but maintained elastic behaviour throughout the loading cycles, even at higher load levels. This elastic response allowed the AFRP tendon joints to exhibit superior self-centering capabilities, with minimal residual displacements observed upon unloading. However, the lack of plastic deformation in AFRP tendons resulted in lower energy dissipation compared to their steel counterparts, highlighting the need for optimization.

To address this limitation, extensive parametric studies were conducted to investigate the effects of varying prestressing forces and damper dimensions on the performance of AFRP tendon joints. The findings indicated that increasing the prestressing force improved initial stiffness and self-centering abilities, albeit with a risk of tendon rupture at excessively high stress levels. Adjustments to the damper leg width, on the other hand, proved to be a more effective strategy for enhancing energy

dissipation while maintaining self-centering performance. The optimal damper leg width was identified to be in the range of 20-21 mm, striking a balance between maximizing energy absorption and preserving the self-centering capabilities of the AFRP tendon joints.

The outcomes of this research contribute significantly to advancing the understanding of SCPC joint behaviour under seismic loading and provide valuable insights into the potential use of AFRP tendons as a promising alternative to traditional steel tendons. The optimized design recommendations derived from this study can facilitate the wider adoption of SCPC technology in construction, promoting the development of more resilient built environments in seismic-prone regions worldwide.

ACKNOWLEDGMENT

Before I commence with the presentation of this study, it is imperative that I express my gratitude to all the individuals whose contributions were indispensable in bringing this work to fruition. Foremost, I would like to express my heartfelt gratitude to God for the wisdom, strength, and inspiration provided throughout the course of this research.

This attempt owes its origin mainly due to the motivation and support I received from my esteemed mentor and guide, Dr. Nirendra Dev, Professor, Delhi Technological University. His words of encouragement, the knowledge he has imparted and the unwavering commitment he has shown have been instrumental in enabling me to achieve this remarkable feat. In consider myself fortunate to have such an exceptional mentor and role model in my life. Without his support, this monumental task would never have come to fruition. I extend my deepest appreciation and heartfelt thanks to my respectful mentor.

I want to thank my respected parents Shri Anil G and Smt Jaya S, who played a pivotal role in consistently encouraging me to pursue my work.

SAJIL A

(2K22/STE/14)

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CHAPTER 1
INTRODUCTION

1.1 GENERAL

Earthquakes pose significant challenges to the structural integrity of buildings, especially in regions prone to seismic activity. While traditional reinforced concrete (RC) frames are designed to resist collapse under seismic loads, they often suffer from extensive damage and residual deformations, impeding post-earthquake recovery efforts. In response to the limitations of conventional seismic design approaches, there has been a paradigm shift towards resilience-based seismic design (RBSD). RBSD emphasizes the importance of not only preventing collapse but also ensuring the rapid recovery of structures and communities after earthquakes

Self-centering structural systems have emerged as promising solutions to enhance the seismic resilience of buildings. Among these systems, Self-Centering Prestressed Concrete (SCPC) frames have garnered attention for their ability to minimize structural damage and residual deformations during seismic events. Unlike traditional cast-in-place frames, SCPC frames utilize prefabricated components assembled onsite using post-tensioned (PT) elements, allowing connections to self-center after seismic disturbances. A key aspect of enhancing the seismic performance of SCPC frames lies in the integration of energy dissipation devices within their connections. These devices are designed to absorb and dissipate seismic energy, thereby reducing the forces transmitted to the structure and minimizing damage.

While SCPC frames offer significant advantages in seismic resilience, challenges remain in optimizing their performance and addressing construction complexities. Ongoing research and innovation aim to develop novel connection designs and energy dissipation devices that enhance the seismic performance of SCPC frames. By advancing our understanding of these systems and their behaviour under seismic loads, researchers seek to promote their widespread adoption and contribute to the development of more resilient built environments.

1.2 RESILIENCE OF A BUILDING

Structural resilience is the ability of a building to endure and quickly recover from adverse events, particularly natural disasters such as earthquakes. A resilient structure can maintain its essential functions and structural integrity during and after such events, ensuring the safety of occupants, minimizing damage, and facilitating rapid recovery. This concept not only encompasses survival but also emphasizes the ability to function with minimal disruption and quickly return to pre-event conditions. Improving the resilience of buildings is essential for several reasons. Firstly, it ensures the safety and well-being of occupants during and after a disaster. Secondly, resilient buildings reduce economic losses by minimizing the need for extensive repairs and downtime. This is particularly critical for essential infrastructure, such as hospitals, emergency response centres, and residential buildings. Finally, enhancing resilience contributes to the overall stability and sustainability of communities, enabling faster recovery and reducing the societal impacts of disasters.

Various methods are employed to improve the resilience of buildings such as:

- Retrofitting: Strengthening existing structures using advanced materials and techniques to enhance their ability to withstand seismic forces.
- Base Isolation: Installing isolation systems at the building's foundation to absorb seismic energy and reduce the transmission of ground motion to the structure.
- Energy Dissipation Devices: Implementing various types of dampers, such as viscous, friction, or tuned mass dampers, to dissipate seismic energy and reduce structural vibrations.
- Advanced Construction Methodologies: Adopting construction methodologies that focus on achieving specific performance objectives under different seismic scenarios, ensuring that buildings meet desired resilience standards. Eg:- Self Centering Systems

Self-centering systems are a pivotal method for enhancing the resilience of buildings. These systems utilize post-tensioned (PT) elements and dampers that allow structures to undergo controlled movements during seismic events and re-center themselves afterward.

1.3 SELF CENTERING SYSTEMS

The quest for earthquake-resistant structures has led to the evolution of self-centering systems, which represent a paradigm shift in seismic engineering. These systems offer a revolutionary approach to mitigating the impact of seismic events by minimizing structural damage and residual deformations. Among the various self-centering solutions, self-centering prestressed concrete (SCPC) frames stand out for their innovative design and exceptional seismic performance. At the heart of self-centering systems lies a fundamental operational principle that sets them apart from conventional structural systems. Utilizing post-tensioned (PT) elements, SCPC frames are engineered to allow controlled movement during seismic events. This dynamic response enables the structure to dissipate seismic energy while maintaining its overall stability. As the structure rocks open and re-centers, it exhibits remarkable resilience against seismic forces, ensuring minimal damage and rapid post-earthquake recovery. Central to the effectiveness of self-centering systems are energy dissipation mechanisms integrated within their connections. These mechanisms serve a dual purpose of enhancing structural strength and dissipating seismic energy. From traditional mild steel bars to advanced friction dampers, a diverse range of energy dissipation devices has been developed to optimize the seismic performance of self-centering systems. By absorbing and dissipating seismic forces, these mechanisms safeguard the integrity of the structure and minimize the risk of structural failure during earthquakes.

Self-centering systems offer numerous advantages over conventional structural systems such as:

- Minimizing Residual Deformations: Self-centering systems are designed to return to their original position after an earthquake, reducing permanent deformations and ensuring the building remains operational with minimal repair needs.

- Energy Dissipation: These systems incorporate energy dissipation devices, such as friction dampers and yielding steel components, which absorb and dissipate seismic energy, protecting the structural components from damage.
- Enhanced Seismic Performance: By allowing the structure to rock and re-center, self-centering systems reduce the likelihood of catastrophic failure, ensuring that the building can withstand severe seismic events without significant damage.
- Quick Recovery: The minimal residual damage associated with self-centering systems facilitates rapid post-event recovery, allowing buildings to be reoccupied and functional shortly after an earthquake.

In conclusion, the resilience of a building is crucial for ensuring safety, minimizing economic losses, and enabling quick recovery after seismic events. By integrating self-centering systems, buildings can achieve superior seismic performance, maintaining their structural integrity and functionality even in the face of significant earthquakes. These systems, alongside other innovative methods, represent the forefront of efforts to create safer, more resilient built environments. As the field of self-centering systems continues to evolve, there is a growing emphasis on exploring novel approaches to enhance their seismic performance. Research efforts are focused on developing innovative materials, connection designs and energy dissipation mechanisms that can address the inherent challenges of self-centering systems. By pushing the boundaries of engineering innovation, researchers aim to unlock the full potential of self-centering systems and pave the way for a more resilient built environment in seismic-prone regions.

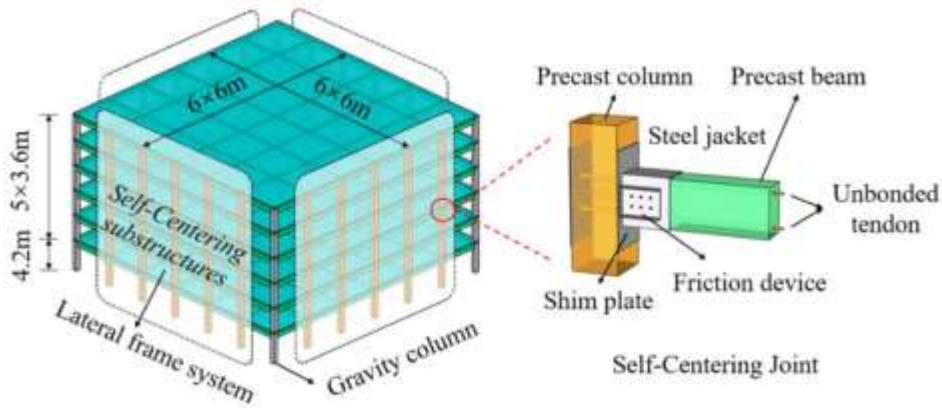

Fig 1.3 Typical SCPC framed structure and joint details

1.4 AFRP

Aramid (aromatic polyamide) is a class of synthetic fibers known for their exceptional strength and heat resistance. These fibers are commonly used in aerospace, military applications, and advanced composites due to their high tensile strength-to-weight ratio. Aramid fibers are typically produced through a polymerization process that creates long molecular chains, resulting in materials that are both lightweight and incredibly strong. Well-known aramid fibers include Kevlar® and Twaron®, which are frequently used in ballistic protection and high-performance applications. Aramid Fiber Reinforced Polymer (AFRP) composites are made by embedding aramid fibers into a polymer matrix, usually epoxy resin, to form a material that harnesses the beneficial properties of both components.

Using AFRP tendons in prestressed concrete offers several advantages over traditional steel tendons:

- Corrosion Resistance: AFRP tendons are inherently resistant to corrosion, making them ideal for use in environments where steel tendons would deteriorate over time, such as in marine or chemically aggressive settings.
- High Strength-to-Weight Ratio: AFRP tendons have a significantly higher strength-to-weight ratio compared to steel, leading to lighter structures without compromising strength. This reduces transportation and handling costs.
- Non-Magnetic and Non-Conductive: AFRP tendons do not interfere with magnetic fields and do not conduct electricity, making them suitable for use in structures sensitive to electromagnetic interference, such as medical facilities or certain industrial applications.
- Superior Fatigue Resistance: AFRP tendons exhibit better fatigue resistance compared to steel, enhancing the durability and lifespan of the prestressed concrete structures in cyclic loading conditions.
- Elastic Behaviour: AFRP tendons exhibit elastic behaviour until failure, providing excellent energy dissipation and self-centering capabilities, which are crucial for seismic applications.

Despite their numerous advantages, AFRP tendons also present some disadvantages when compared to steel:

- Higher Initial Cost: The initial cost of AFRP tendons is generally higher than that of steel tendons, which can be a deterrent for widespread adoption despite potential long-term savings due to reduced maintenance.
- Lower Modulus of Elasticity: AFRP tendons have a lower modulus of elasticity compared to steel, leading to larger deflections under load. This requires careful design considerations to ensure structural performance.
- Susceptibility to Creep: AFRP materials can exhibit creep under sustained loads, which must be accounted for in long-term structural performance.
- Brittle Failure Mode: AFRP tendons can fail in a brittle manner without significant prior deformation, necessitating precise quality control and monitoring during installation and use.
- Limited Field Experience: The use of AFRP tendons in construction is relatively new compared to steel, resulting in less field experience and established best practices.

1.5 OBJECTIVES OF THE STUDY

The main objectives of the study are:

- To assess the behaviour of SCPC joints under cyclic loading
- To investigate the differences in mechanical properties and seismic performance between steel and AFRP tendons when used in SCPC joints
- To compare the performance of SCPC joints using steel tendons versus AFRP tendons in terms of load-bearing capacity, energy dissipation, and residual deformations.
- To determine the advantages and limitations of using AFRP tendons compared to traditional steel tendons in self-centering applications.
- To optimize Pre-Stressing Force for AFRP Tendons
- To Develop and Validate a Numerical Model for SCPC Joints

By achieving these objectives, the study aims to provide a comprehensive understanding of the behaviour of SCPC joints under cyclic loads, compare the performance of different tendon materials, and propose design improvements to enhance the seismic resilience of SCPC joints using AFRP tendons.

1.5 ORGANIZATION OF THESIS

- Chapter 1 Gives a concise explanation of SCPC frames and outlines the goals of the research as well as the parameters of the study.
- Chapter 2 Provides a comprehensive literature review associated with SCPC frame and recent investigations in SCPC frame
- Chapter 3 Describes the methodology used and provides information on the materials and numerical analysis procedure
- Chapter 4 Presents the results of the experimental work and discussions of the outcomes.
- Chapter 5 Address the findings of the present study and some recommendations for potential future research.

CHAPTER 2
LITERATURE REVIEW

The field of seismic resilience in structural engineering has seen notable progress with the development of self-centering prestressed concrete (SCPC) systems. Over recent decades, SCPC frames have gained attention as a viable alternative to conventional cast-in-place reinforced concrete frames, owing to their superior seismic performance characterized by minimal residual deformations and reduced structural damage post-earthquake. This chapter offers an extensive overview of the latest research on SCPC systems, emphasizing various advancements and experimental studies that aim to enhance their efficacy.

Liang-long Song et al. (2013) investigate the development and experimental validation of a self-centering prestressed concrete (SCPC) moment resisting frame (MRF) connection that incorporates bolted web friction devices (WFDs). This innovative system merges the benefits of post-tensioned precast concrete MRFs and self-centering steel MRFs, enhancing seismic performance and energy dissipation. The SCPC connection with bolted WFDs introduces significant improvements, such as substituting welded connections with bolted ones, utilizing aluminum plates for friction, and reconfiguring post-tensioned tendons. Experimental validation, including cyclic tests and numerical simulations with OpenSees, confirms that these enhancements effectively improve the seismic performance of SCPC connections. The SCPC connection with bolted WFDs, when designed according to the provided guidelines, shows self-centering and energy dissipation capabilities comparable to those of traditional welded WFDs.

Yadong Li et al. (2020) introduced a low-damage self-centering precast concrete (LDSCPC) frame connection that features replaceable dampers, aiming to enhance seismic resilience and minimize repair costs. This system employs precast components with embedded steel connectors and post-tensioned tendons, providing flexibility for upgrades and expansions. Cyclic load tests comparing LDSCPC and traditional reinforced concrete (RC) frame joints demonstrated that LDSCPC joints have superior mechanical performance, exhibiting excellent self-centering ability and minimal damage. The LDSCPC joints maintained stable behavior, achieving stress levels similar to RC joints but at much higher deformations with only minor surface cracks in the concrete. A detailed finite element (FE) model confirmed the experimental findings, showcasing the LDSCPC joint's behavior under seismic loads. Further parametric studies on the dampers offered insights into their impact on joint performance and provided design recommendations to enhance seismic resilience.

Xiaoning Cai et al. (2020) aimed to improve seismic resilience in precast concrete structures by developing an innovative self-centering prestressed concrete frame that incorporates post-tensioning tendons and steel angles. They conducted both experimental and numerical studies on a half-scale frame subassembly to evaluate its seismic performance. The results indicated that the precast members and tendons behaved elastically, while the steel angles contributed to energy dissipation. The study also assessed the repairability of the structure, finding that it maintained comparable performance after repair due to the minimal damage incurred. Numerical simulations using OpenSees revealed that increasing the initial post-tensioning force and the area of the tendons enhanced the stiffness and load-carrying capacity of the subassembly. Conversely, reducing the thickness of the steel angles or increasing the column gauge length diminished the energy dissipation capacity of the structure.

Linjie Huang et al. (2021) investigated the seismic performance of post-tensioned self-centering precast concrete (SCPC) frames equipped with variable friction dampers (VFDs) and hidden corbels (HCs). VFDs, made of flat and grooved plates, modify friction forces in response to deformation, thereby meeting different seismic performance requirements across various hazard levels. The research developed theoretical and numerical models for these connections, facilitating a performance-based seismic design approach for SCPC frames. The study proposed a design procedure for SCPC frames in high seismic regions, using HC-VFD-SCPC connections to address drift concentration issues in the first story. Nonlinear time-history analyses with ground motions representing design basis earthquake (DBE) and maximum considered earthquake (MCE) levels demonstrated that frames with HC-VFD-SCPC connections achieved performance objectives and reduced drift demands more effectively than those with constant friction devices (CFDs). This comprehensive analysis highlights innovative seismic design strategies, emphasizing the benefits of VFDs and HC-VFD-SCPC connections in improving seismic performance. Additionally, quasi-static cyclic tests of HC-VFD-SCPC beam-to-column connections were performed to validate the numerical model.

Linjie Huang et al. (2022) conducted a study to evaluate the seismic performance and resilience of friction-based self-centering prestressed concrete (SCPC) frames. Through experimental and dynamic analyses, the behavior of friction-damped SCPC (FD-SCPC) frames under fortification and rare earthquakes was assessed. The study revealed that these frames possess recentering capacity, minimized damage, and enhanced seismic performance compared to traditional concrete frames. Specifically, a friction-based SCPC frame was designed for seismic analysis under an eight-degree seismic fortification intensity in China, ensuring the structures met different performance objectives under various ground motion intensities.

For the nonlinear dynamic analyses, fifteen ground motions with varying characteristics were used, and parameters like inter-story drift were considered for damage evaluation. Ground motions were scaled to both fortification and rare earthquake levels to compare the seismic responses of different frame types. The FD-SCPC frames demonstrated the anticipated hysteretic behavior with recentering capacity and reduced damage to structural components, akin to cast-in-place reinforced concrete frames during fortification earthquakes. During rare earthquakes, the unique rocking mechanism and frictional energy dissipation resulted in significantly less damage to FD-SCPC frames compared to traditional concrete frames. Overall, the seismic performance and resilience of FD-SCPC frames were found to be superior, considering both the repair cost and time for structural and non-structural components.

Jule Zheng et al. (2022) explored the seismic resilience of Self-Centering Prestressed Concrete (SCPC) frames, emphasizing the roles of energy dissipation ratio and second stiffness. Their study involved dynamic parametric analyses under various earthquake intensities and fragility analyses across different performance levels. A novel approach, the MD-RD joint probability density method, was introduced to analyze the damage distribution in both structural and non-structural members of SCPC structures. The research examined the impact of energy dissipation ratio and second stiffness on the resilience of SCPC frameworks using the FEMA P-58 resilience assessment framework. Findings indicated that increasing the second stiffness reduced the effects of higher-order modes and decreased losses in the upper sections of SCPC frames. Additionally, a higher energy dissipation ratio led to a reduced maximum structural response and improved overall building resilience. Through incremental dynamic analysis, fragility curves for SCPC frames were generated, illustrating the influence of different energy dissipation ratios on structural vulnerability across various performance levels. The study also compared the seismic performance of SCPC frames with varying energy dissipation ratios, noting changes in maximum drift responses at different earthquake intensity levels.

Xueyuan Yan et al. (2023) investigated the mechanical behavior of a self-centering joint between a concrete-filled double steel tubular (CFDST) column and a reinforced concrete (RC) beam. This joint is designed to enhance repairability and reusability after sustaining damage, addressing a common issue in traditional connections. The joint utilizes prestressed steel strands for self-centering and incorporates friction for energy dissipation. The study validated the accuracy of numerical models by comparing them with theoretical values. Key parameters analyzed numerically included friction, the prestress level of the steel strands, and the ratio of resisting moments. The material properties were critical to the analysis, employing a bilinear stress-strain model for steel and a concrete damage-plasticity model for concrete. Finite element software was used for the numerical analysis, with theoretical formulas serving as validation tools. The dimensions and stiffness of the joint were found to be crucial in determining its behavior under load. The numerical analysis showed that joints with higher friction and increased prestress in the steel strands demonstrated greater bearing capacity. While increased friction improved energy dissipation, it also led to higher residual deformation, which could be mitigated by increasing the prestress in the steel strands.

Xinyu Hu et al. (2023) assessed the hysteretic performance of prestressed concrete beams reinforced with aramid fiber-reinforced polymer (AFRP) tendons through experimental and finite element (FE) analysis. The study explored the impact of various factors, including the type of prestressing tendons, the ratio of internal to external tendons, and the bond conditions of internal tendons, on the behavior of the beams. The research demonstrated that AFRP prestressed beams have comparable bearing capacity, displacement ductility, energy dissipation, and residual deformation to those reinforced with steel tendons. The findings indicated that using a combination of internal and external tendons, as well as employing unbonded or partially bonded tendons, could enhance the ductility of AFRP prestressed beams. The primary failure mode observed in all beams was flexural failure, characterized by concrete crushing and the rupture of non-prestressed rebars at the pure bending sections. Moreover, combining internal and external tendons in AFRP prestressed beams significantly improved both positive and negative ductility coefficients compared to beams with only internal tendons. Parametric predictions showed that increasing the unbonded length of the AFRP tendons reduced bearing capacity and residual deformation ratio but enhanced the ductility of the FE models.

The reviewed literature demonstrates the substantial progress made in the field of self-centering prestressed concrete (SCPC) systems. These studies collectively underscore the potential of SCPC frames to significantly improve seismic performance by minimizing residual deformations and structural damage.

RESEARCH GAPS

- The long-term performance of SCPC joints under sustained loads and cyclic fatigue including aspects like creep, shrinkage and stress relaxation of concrete and prestressing tendons needs further investigation
- Although various energy dissipation devices are integrated into SCPC joints, further research is needed to optimize their performance in terms of energy absorption, stability, and constructability

- Exploring and optimizing the use of innovative materials like high-performance concrete, fiber-reinforced polymers, and shape memory alloys can further enhance the joint's strength, durability, and self-centering capability
- Developing efficient and cost-effective prefabrication and assembly techniques for SCPC joints can facilitate wider adoption of this technology in construction
- Investigating the influence of non-structural components, such as infill walls and partitions, on the seismic behavior of SCPC frames is crucial for ensuring the overall structural integrity
- Exploring the use of SCPC technology for other structures beyond buildings, such as bridges and offshore platforms

CHAPTER 3
METHODOLOGY

3.1 GENERAL

In this chapter, the methodology employed to investigate the seismic performance of Self-Centering Precast Concrete (SCPC) joints using cyclic testing in Abaqus software is presented.

This chapter outlines the materials, modelling techniques, loading conditions, and optimization strategies used in the study, providing a comprehensive framework for understanding the seismic behaviour of SCPC joints.

3.2 MATERIALS

This subsection details the various materials used in the development and analysis of the SCPC joint models. Each material's properties play a crucial role in the accuracy and reliability of the finite element simulations performed in Abaqus.

3.2.1 M50 CONCRETE

Usage: Used for the beam and column components of the SCPC joint.

Properties:

Sl. No.	Property	Value
1	Compressive Strength (MPa)	50
2	Density (kg/m^3)	2400
3	Young Modulus (MPa)	51000
4	Poisson's ratio	0.19
5	Dilation angle	38
6	Eccentricity	1
7	fb0/fc0	1.12
8	K	0.666
9	Viscosity parameters	0.001

Table 3.2.1.1 Properties of M50 Concrete

Compressive behaviour		Compression damage	
Yield stress	Inelastic strain	Damage parameter	Inelastic strain
15	0	0	0
20.197804	7.47307E-05	0	7.47307E-05
30.000609	9.88479E-05	0	9.88479E-05
40.303781	0.000154123	0	0.000154123
50.007692	0.000761538	0	0.000761538
40.23609	0.002557559	0.195402	0.002557559
20.23609	0.005675431	0.596382	0.005675431
5.257557	0.011733119	0.894865	0.011733119
Tensile behaviour		**Tension damage**	
Yield stress	**Cracking strain**	**Damage parameter**	**Cracking strain**
1.99893	0	0	0
2.842	0.00003333	0	0.00003333
1.86981	0.000160427	0.406411	0.000160427
0.862723	0.000279763	0.69638	0.000279763
0.226254	0.000684593	0.920389	0.000684593
0.056576	0.00108673	0.980093	0.00108673

Table 3.2.1.2 Concrete Damage Plasticity Values

3.2.2 HRB400 STEEL REINFORCEMENT

Usage: Reinforcement within the concrete beam and column.

Properties:

Sl. No.	Property	Value
1	Yield Strength (MPa)	400
2	Density (kg/m^3)	7850
3	Young Modulus (MPa)	200000
4	Poisson's ratio	0.3
5	Ultimate Strength	540

Table 3.2.2 Properties of HRB400 Steel

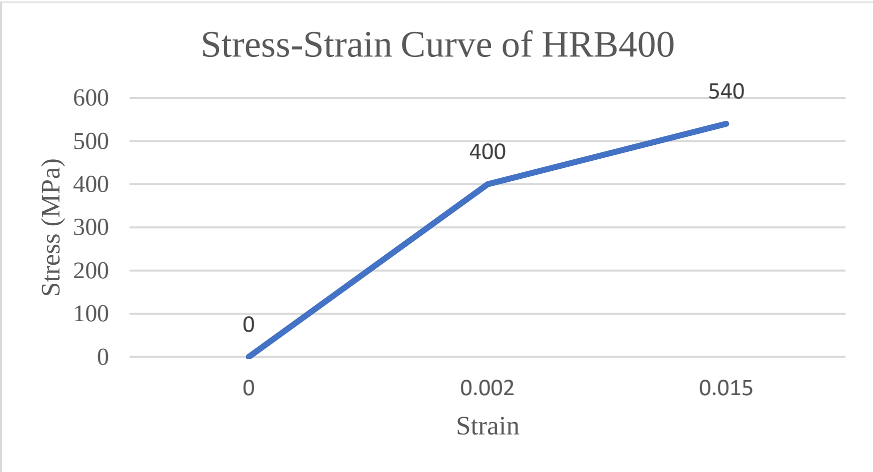

Fig.3.2.2 Bilinear Stress-Strain Curve of HRB400 steel

3.2.3 Q345B STEEL

Usage: Used for the column and beam connectors.

Properties:

Sl. No.	Property	Value
1	Yield Strength (MPa)	345
2	Density (kg/m^3)	7850
3	Young Modulus (MPa)	200000
4	Poisson's ratio	0.3
5	Ultimate Strength	470

Table 3.2.3 Properties of Q345B Steel

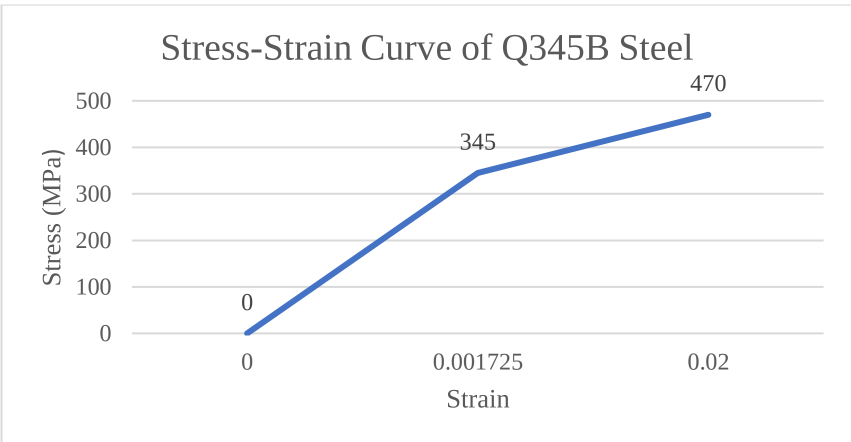

Fig.3.2.3 Bilinear Stress-Strain Curve of Q345B steel

3.2.4 Q235B STEEL

Usage: Used for the damper components.

Properties:

Sl. No.	Property	Value
1	Yield Strength (MPa)	235
2	Density (kg/m^3)	7850
3	Young Modulus (MPa)	200000
4	Poisson's ratio	0.3
5	Ultimate Strength	370

Table 3.2.4 Properties of Q235B Steel

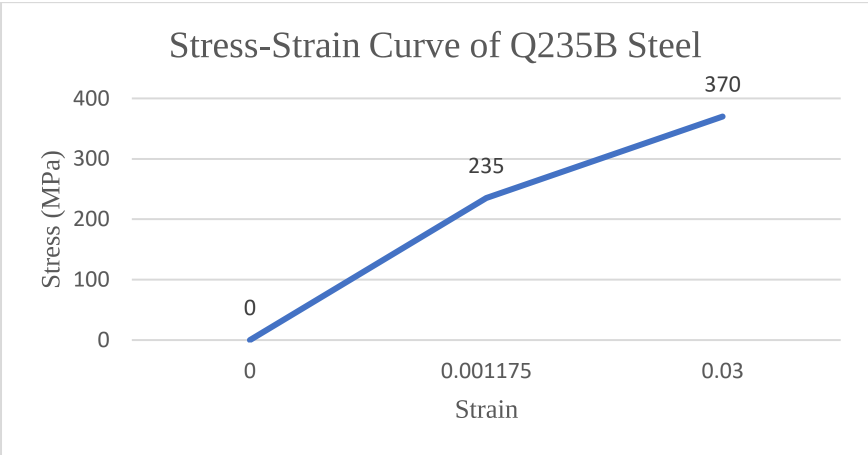

Fig.3.2.4 Bilinear Stress-Strain Curve of Q235B steel

3.2.5 M20 REAMING BOLTS OF GRADE 10.9

Usage: Used for connecting damper to the connectors.

Properties:

Sl. No.	Property	Value
1	Yield Strength (MPa)	940
2	Density (kg/m^3)	7850
3	Young Modulus (MPa)	210000
4	Poisson's ratio	0.3
5	Ultimate Strength	1040

Table 3.2.5 Properties of Bolt

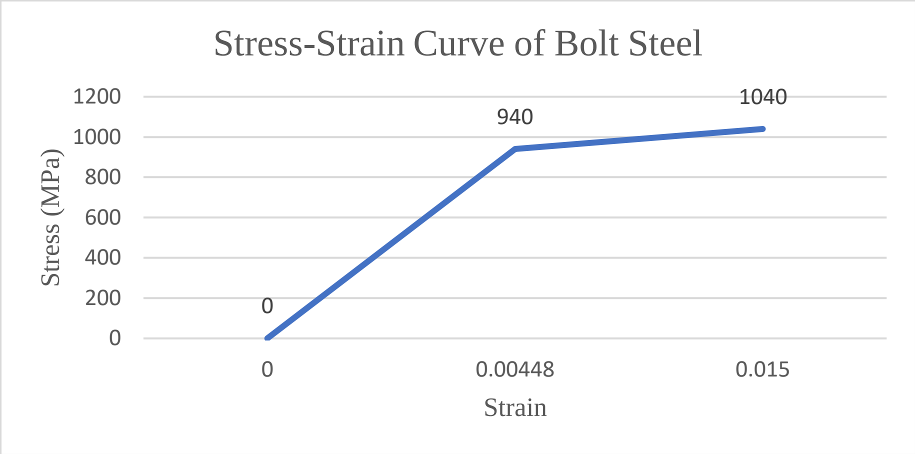

Fig.3.2.5 Bilinear Stress-Strain Curve of Bolt steel

3.2.6 STEEL TENDONS

Usage: For Pre-Stressing the joint

Properties:

Sl. No.	Property	Value
1	Yield Strength (MPa)	1600
2	Density (kg/m^3)	7850
3	Young Modulus (MPa)	200000
4	Poisson's ratio	0.3
5	Ultimate Strength	1860

Table 3.2.6 Properties of Steel Tendon

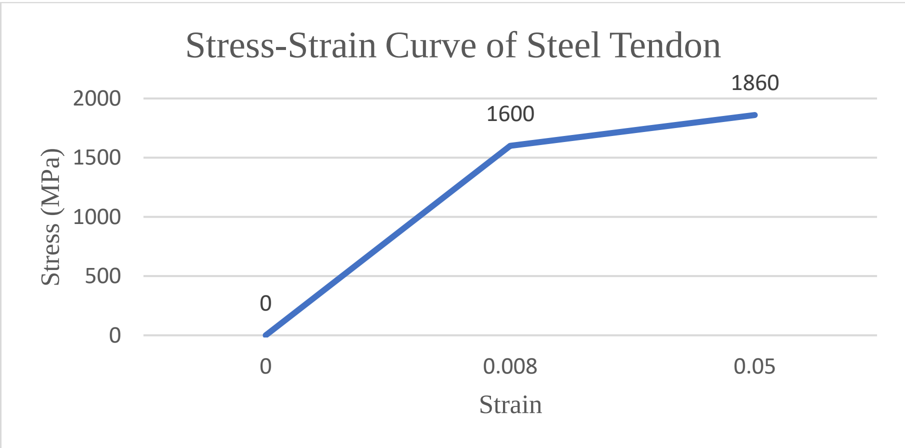

Fig.3.2.2 Bilinear Stress-Strain Curve of Steel Tendon

3.2.7 AFRP TENDONS

Usage: For Pre-Stressing the joint

Properties:

Sl. No.	Property	Value
1	Yield Strength (MPa)	-
2	Density (kg/m^3)	1300
3	Young Modulus (MPa)	54000
4	Poisson's ratio	0.35
5	Ultimate Strength	1900

Table 3.2.7 Properties of AFRP Tendon

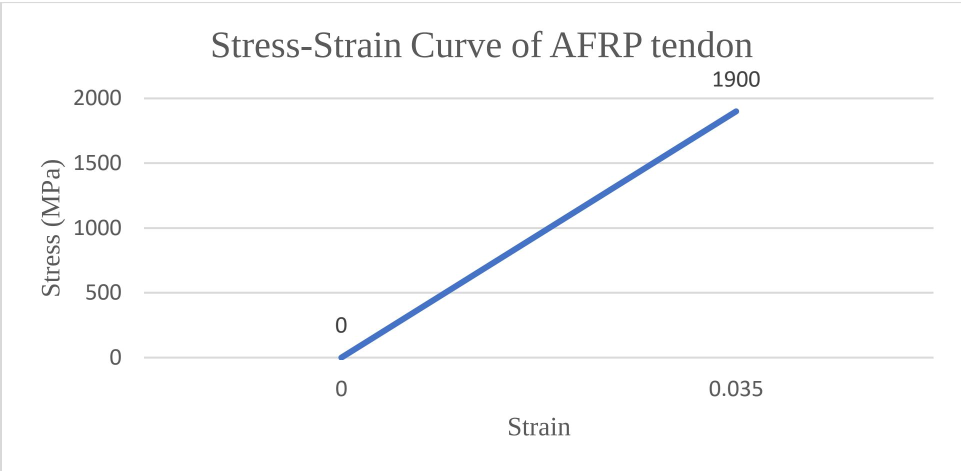

Fig.3.2.7 Stress-Strain Curve of AFRP Tendon

3.3 MODELLING

The modelling will be conducted using Abaqus software, which will facilitate the simulation of the structural behaviour under the specified loading conditions. The objective is to validate the model against experimental data and subsequently compare the performance of steel and aramid fiber-reinforced polymer (AFRP) tendons. Additionally, we will explore the optimization of the SCPC joint by adjusting the prestressing force and damper dimensions to enhance energy dissipation.

3.3.1 PARTS AND DIMENSIONS

- **Beam and Column**

  The dimensions of column and beam of M50 grade concrete are provided in figure below. Four ducts of 25mm diameter are provided in column and beam as shown in the figure to accommodate the pre-stressing tendons.

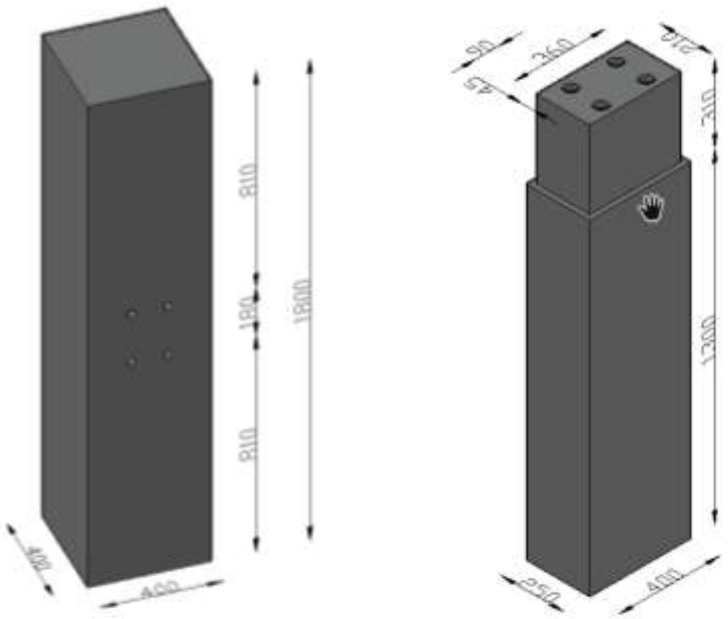

Fig.3.3.1.1 Column and Beam dimensions

- **Column Connector**

  The dimensions of column connector made of Q345B grade steel are given in figure below. The flanges are of 10mm thick plates and web is of 20mm thick plate. Four holes of 25 mm diameter are provided in flange to accommodate the pre-stressing tendons and four holes of 21mm diameter are provided in web for connection purposes. Column connector is partially embedded in the column.

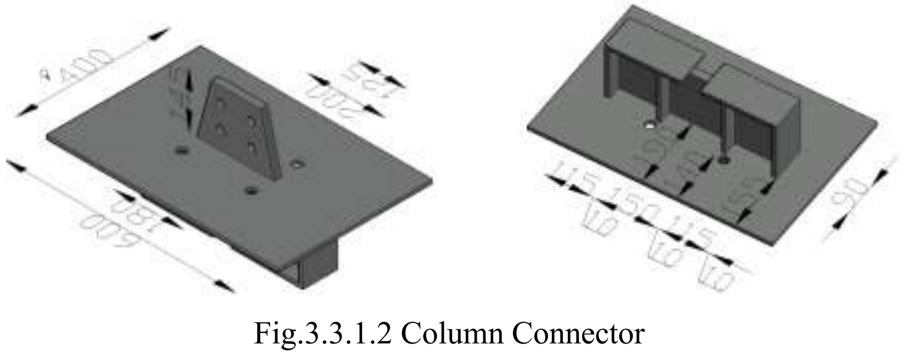

Fig.3.3.1.2 Column Connector

- **Beam Connector**

  The dimensions of beam connector made of Q345B grade steel are given in figure below. It is fully made of 20mm thick plate. Four holes of 25 mm diameter are provided to accommodate the pre-stressing tendons and four holes of 21mm diameter are provided for connection purposes. Beam end is inserted into the beam connector.

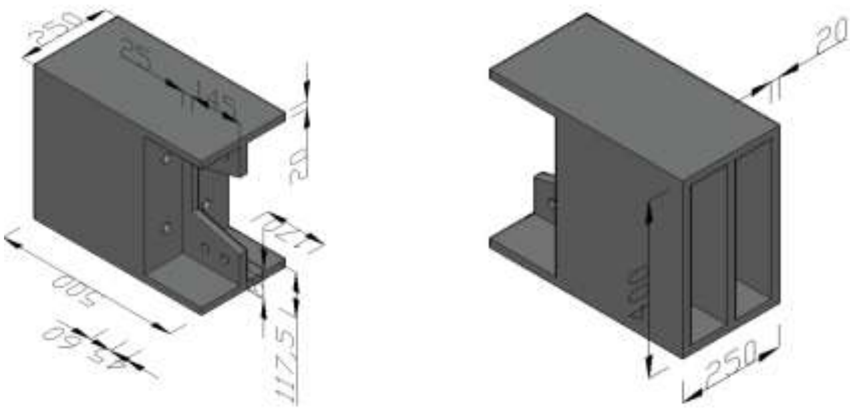

Fig.3.3.1.3 Beam Connector

- **Damper and Bolt**

  The dimensions of damper made of Q345B grade steel and M20 reaming bolts of grade 10.9 are given in figure below. The damper is of 12mm thick. Four holes of 21mm diameter are provided for connection purposes. One end of the damper is connected with column connector and the other end with beam connector.

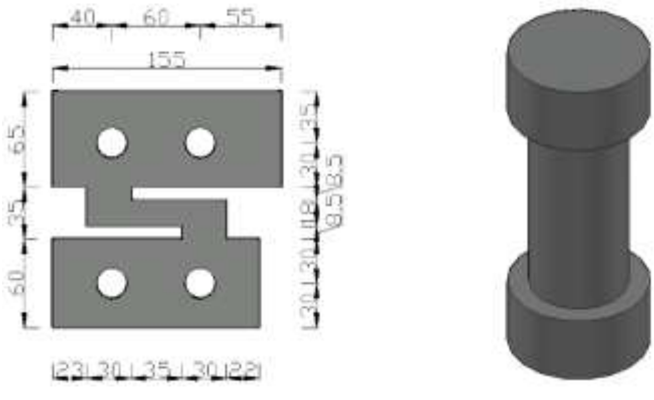

Fig.3.3.1.4 Damper and Bolt

- **Column Reinforcement**

  The column reinforcement is of HRB400 grade steel. The column is provided with 12 nos. of 16mm diameter bar equally distributed along the cross section of the column as longitudinal reinforcement and six legged ties of 8mm diameter at a spacing of 100mm as lateral reinforcement.

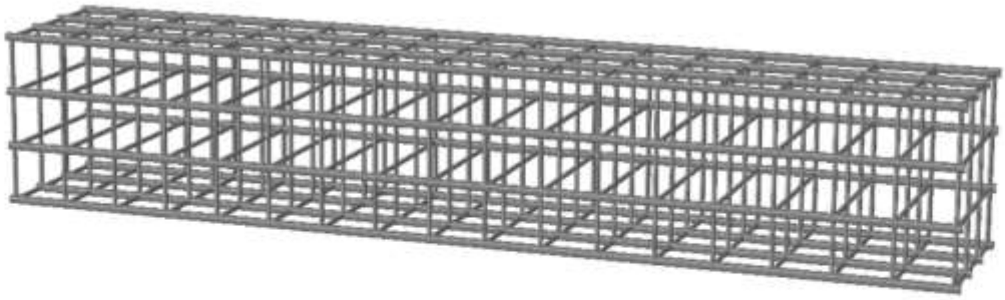

Fig.3.3.1.5 Column Reinforcement

- **Beam Reinforcement**

  The beam reinforcement is of HRB400 grade steel. The beam is provided with 3 nos. of 14mm diameter bar each at top and bottom as longitudinal reinforcement and two legged stirrups of 8mm diameter at a spacing of 100mm as lateral reinforcement.

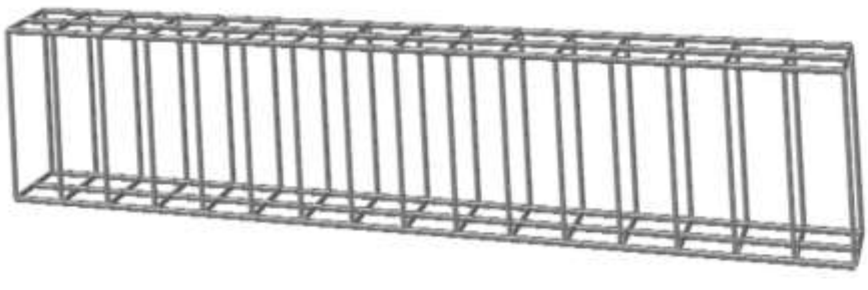

Fig.3.3.1.6 Beam Reinforcement

- **Pre-stressing Tendons (PT Tendons)**

  Four PT tendons of nominal diameter 15.2 mm, and the effective cross-sectional area of 140 mm^2 are provided through the ducts in beam and column and are anchored to the outer face of column and end of beam. Two different types of tendons made of steel and AFRP are used. The length of tendons is 2210mm. A prestressing force of 1600 kN is applied initially.

3.3.2 ASSEMBLY

All the parts are assembled as shown in Fig.3.3.2

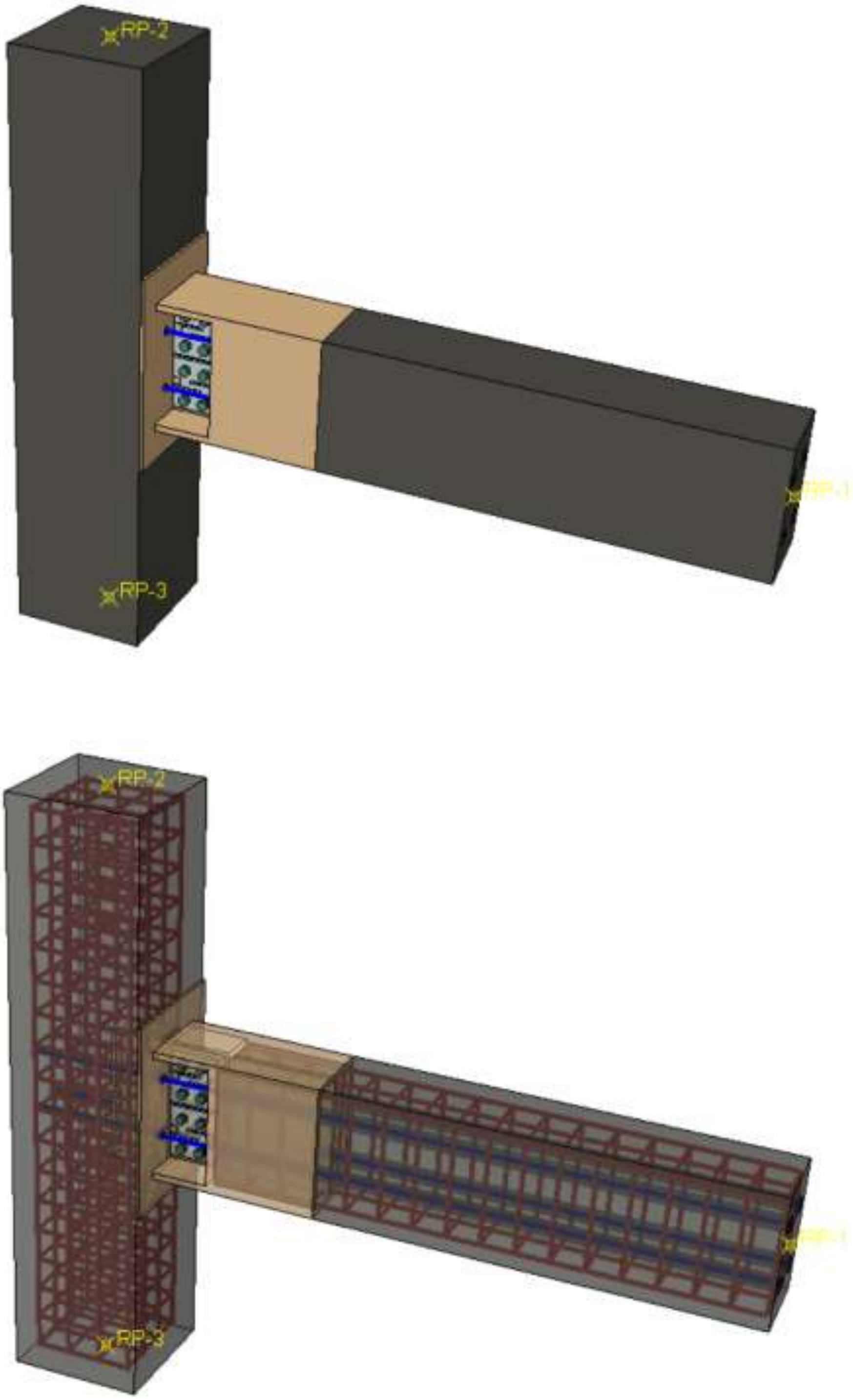

Fig.3.3.2 Assembled Joint

3.3.3 BOUNDARY CONDITIONS

Properly defining the boundary conditions is crucial to ensure the accuracy of the simulation results.

- **Column Boundary Conditions**

  To simulate the real-world constraints and supports of the SCPC joint during testing, the ends of the column are fixed. This setup represents the foundation conditions of a typical structural frame and restricts all degrees of freedom, ensuring that the column base remains stationary and mimics the behaviour of the column embedded in the foundation. The ends of the column are fully constrained to prevent any movement or rotation. This means that translations and rotations in all directions (x, y, and z) are restricted, effectively fixing the column to the ground.

- **Reference Point**

  For accurate measurement of deflections and to apply the cyclic loading, a reference point is created at the end of the beam. This reference point is strategically positioned to provide a clear and direct measurement of the beam's response to the applied loads. A reference point is placed at the centre of the end face of the beam. This point is crucial for both applying the cyclic loads and recording the deflection values during the simulation. It allows for a simplified and accurate representation of the load application and response measurement. The reference point is coupled to the centre of the end face of the beam using a kinematic coupling constraint. This ensures that the reference point accurately represents the motion of the beam's end face. The coupling constraint makes the reference point and the end face of the beam move together, maintaining their relative positions and orientations.

3.3.4 LOADING CONDITIONS

The cyclic loading is applied to the beam through the reference point to simulate the seismic loads experienced by the SCPC joint. The load is applied in a displacement-controlled manner, replicating the cyclic nature of seismic events. The cyclic load is applied at the reference point in a displacement-controlled manner. This approach ensures that the loading follows a predefined displacement history, which is essential for simulating the cyclic nature of seismic loads. The displacement protocol typically involves a series of increasing and decreasing displacements, replicating the push-pull action experienced during an earthquake.

Cyclic Load Protocol:

The load protocol consists of multiple cycles of increasing amplitude to represent the progressive nature of seismic loading. This protocol is designed to capture the load-displacement response, energy dissipation, and residual deformations of the SCPC joint under cyclic loading conditions.

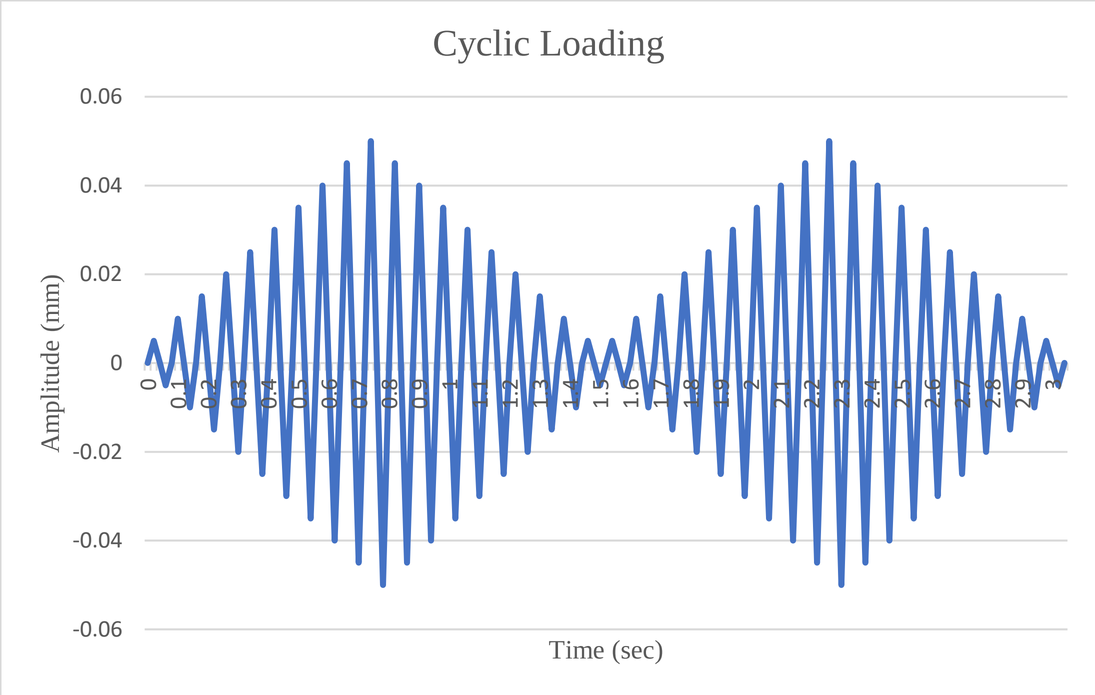

Fig.3.3.4 Cyclic Loading

3.3.5 MESH GENERATION

The accuracy and convergence of finite element analysis heavily depend on the quality of the mesh. For the SCPC joint model in this study, the mesh was generated using tetrahedral elements due to their ability to conform to complex geometries and provide reliable results in analysis. The meshing strategy involved different mesh sizes for various components of the model to balance computational efficiency and accuracy.

- **Mesh Type**

  The mesh was generated using the "Tetrahedral Free" meshing algorithm in Abaqus. This method is particularly suitable for complex geometries like the SCPC joint, allowing for automatic and efficient mesh generation.

- **Mesh Sizes**

  A mesh size of 20 mm was applied to the concrete columns and beams as well as the internal reinforcement. This size was chosen to capture the overall structural response while maintaining a manageable number of elements. A finer mesh size of 10 mm was used for the steel connectors and dampers. This finer mesh ensures that the local stress distributions and interactions at the connection interfaces are accurately captured. An even finer mesh size of 4 mm was applied to the bolts. Bolts are critical components that transfer significant forces, and a finer mesh is necessary to accurately model their behaviour and interactions with surrounding materials.

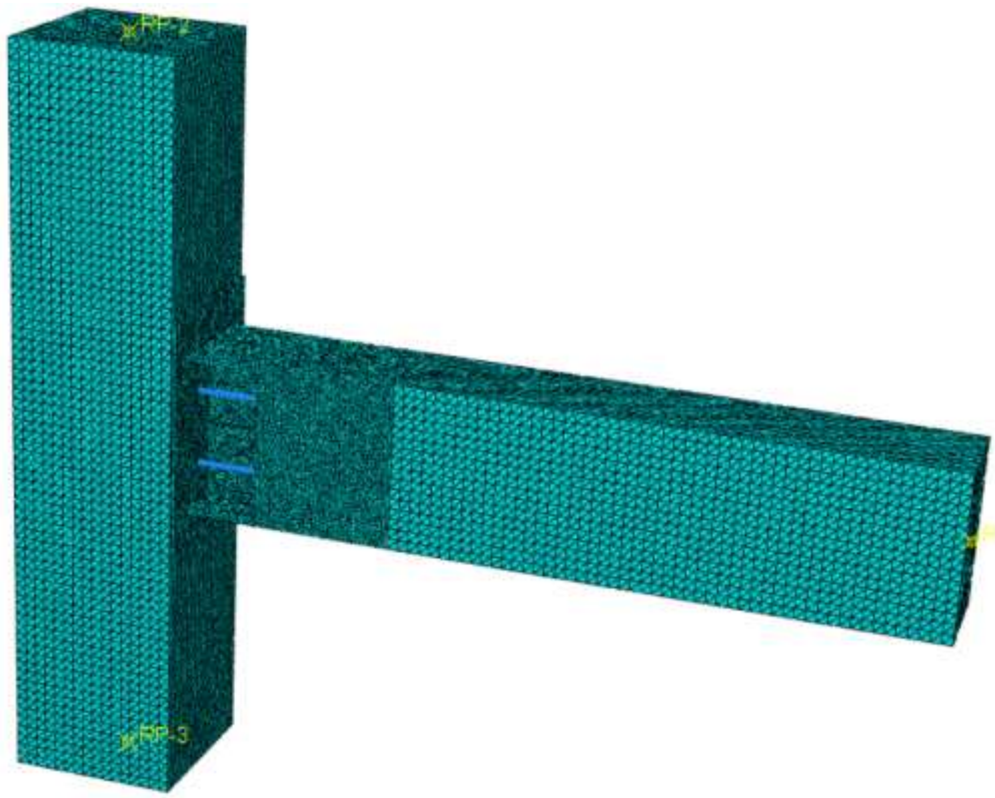

Fig.3.3.5 Meshed Model

CHAPTER 4
RESULT AND DISCUSSION

4.1 GENERAL

In this chapter, we present and analyse the results obtained from the cyclic loading tests on Self-Centering Precast Concrete (SCPC) joints. The primary objective is to compare the performance of SCPC joints when reinforced with steel tendons versus Aramid Fiber Reinforced Polymer (AFRP) tendons. This analysis includes evaluating the load-displacement behaviour, energy dissipation capacity, residual displacements, and failure modes of the joints. By utilizing Abaqus software for numerical simulations, the aim is to replicate real-world conditions and validate the model against experimental data. The study extends to optimizing the SCPC joints with AFRP tendons by adjusting prestressing force to address identified limitations and enhance overall performance. The findings from these simulations provide insights into the structural behaviour of SCPC joints under seismic loading and highlight potential improvements in seismic resilience and post-earthquake repairability.

4.2 LOAD-DISPLACEMENT BEHAVIOUR

The load-displacement behaviour of Self-Centering Precast Concrete (SCPC) joints under cyclic loading is a crucial indicator of their performance and resilience, particularly in seismic applications. This subsection provides a detailed analysis of the load-displacement curves obtained from the cyclic tests, focusing on the differences between SCPC joints with steel tendons and those with Aramid Fiber Reinforced Polymer (AFRP) tendons.

4.2.1 STEEL TENDONS

The SCPC joints with steel tendons displayed a characteristic load-displacement behaviour typical of ductile materials. The following observations were made:

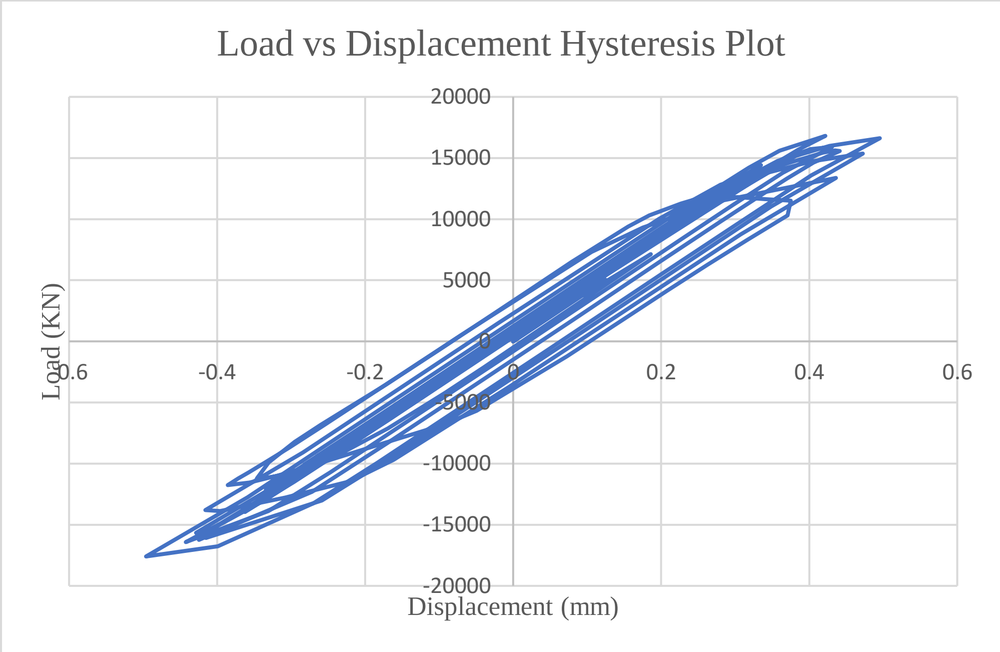

Fig.4.2.1.1 Load vs Displacement Curve

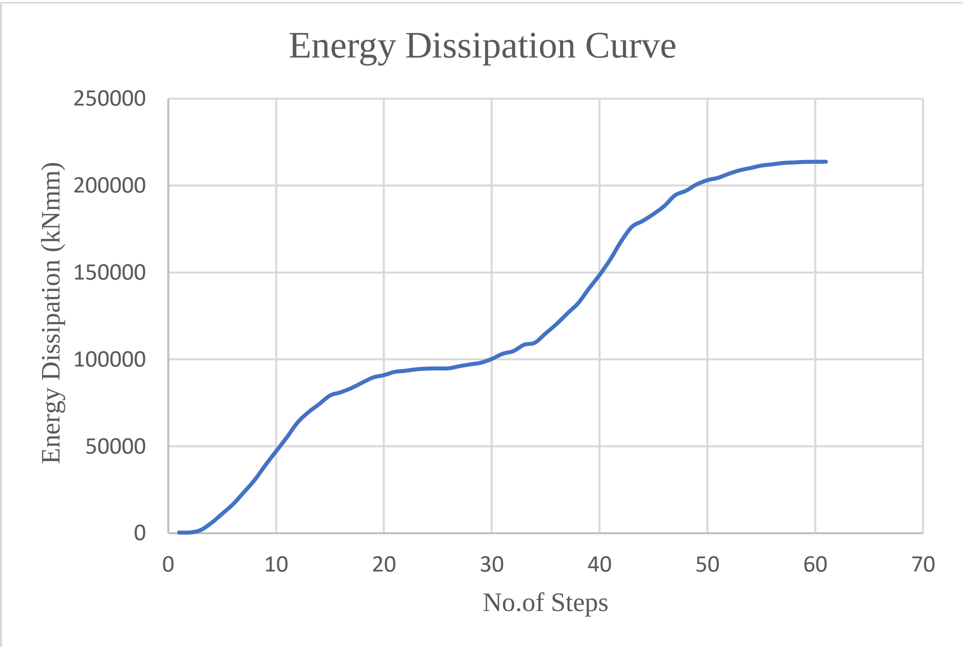

Fig.4.2.1.2 Energy Dissipation Curve

- **Initial Stiffness:** The initial stiffness of the SCPC joints with steel tendons was relatively high, indicating robust resistance to initial loading. This stiffness is primarily due to the high modulus of elasticity of steel.
- **Yielding and Plastic Deformation:** As the loading increased, the steel tendons began to yield, leading to plastic deformation. The yielding point was evident on the load-displacement curve as a transition from a linear to a nonlinear response.
- **Energy Dissipation:** The area under the hysteresis loops of the load-displacement curves represents the energy dissipated during each loading cycle. The steel tendons, through their plastic deformation, dissipated a significant amount of energy, which is beneficial for seismic applications as it reduces the energy transmitted to the rest of the structure.
- **Residual Displacement:** After unloading, the SCPC joints with steel tendons exhibited some residual displacement. This residual deformation is a result of the permanent plastic deformation of the steel tendons, which can lead to post-earthquake repair requirements.

4.2.2 AFRP TENDONS

The load-displacement behaviour of SCPC joints with AFRP tendons showed distinct differences from those with steel tendons:

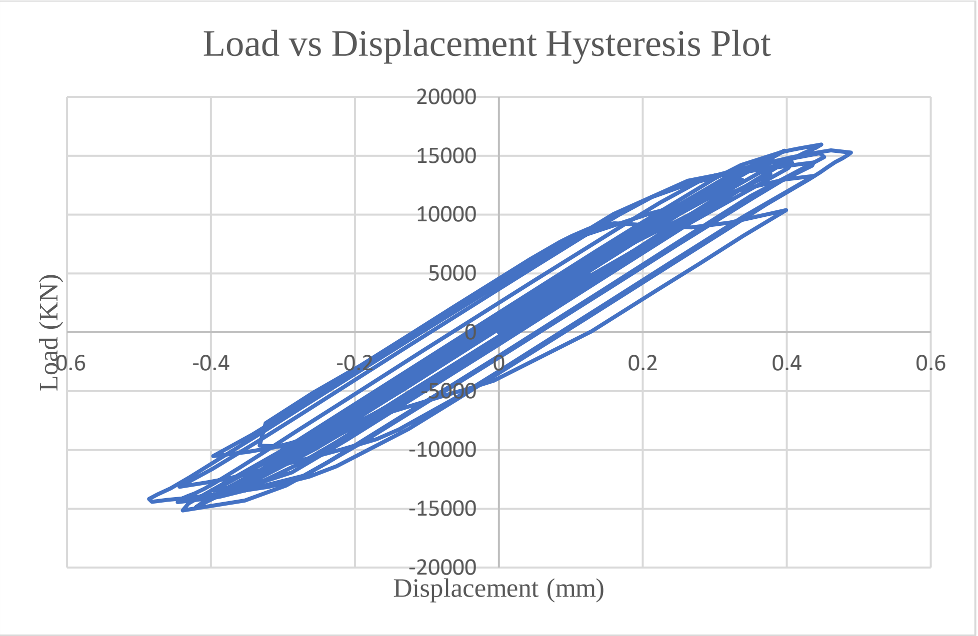

Fig.4.2.2.1 Load vs Displacement Curve

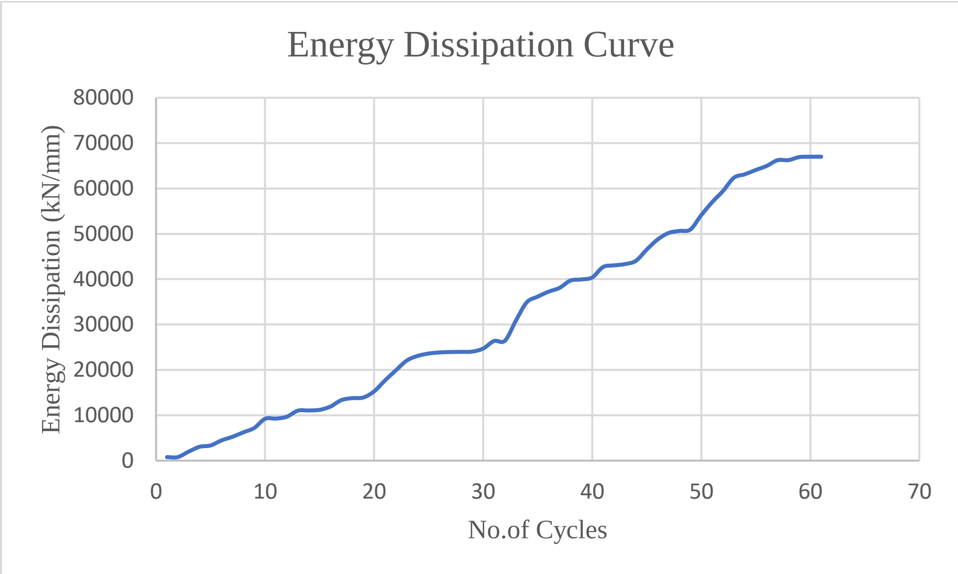

Fig.4.2.2.2 Energy Dissipation Curve

- **Initial Stiffness:** The initial stiffness of the AFRP tendon joints was comparable to that of the steel tendon joints, indicating a similar initial resistance to loading. This similarity is due to the high tensile strength and modulus of AFRP tendons.
- **Elastic Behaviour:** Unlike steel tendons, AFRP tendons do not exhibit yielding and remain elastic up to their failure point. This behaviour was reflected in the load-displacement curves, which maintained a linear relationship up to higher load levels compared to steel tendons.
- **Energy Dissipation:** The AFRP tendons do not dissipate energy through plastic deformation. Instead, energy dissipation in these joints was primarily achieved through the frictional dampers and other energy-absorbing mechanisms within the joint. The overall energy dissipation was lower compared to steel tendons.
- **Self-Centering Capability:** One of the significant advantages of AFRP tendons is their superior self-centering capability. The load-displacement curves showed minimal residual displacement upon unloading, indicating that the joints could return to their original position without significant permanent deformation. This property is highly desirable in seismic applications as it reduces the need for extensive post-earthquake repairs.

4.2.3 OPTIMIZATION OF SCPC JOINT WITH AFRP

In-depth parametric studies were performed to optimize the performance of SCPC joints reinforced with AFRP tendons. These studies focused on varying prestressing forces and damper dimensions to understand their impact on the structural behaviour and energy dissipation characteristics of the joints.

- **Prestressing Force**

Initially, the prestressing force in AFRP tendons was 1600 kN and it is adjusted to enhance the joint's performance. By increasing the prestressing force, the initial stiffness of the joint improved, enhancing its ability to self-center after experiencing loads. This increase in stiffness helps in reducing residual displacements, making the structure more resilient to seismic activities. However, it was found that merely adjusting the prestressing force was insufficient to achieve the desired balance between energy dissipation and self-centering capabilities. Excessive prestressing force (above 1800) led to a risk of tendon rupture due to the high stress levels exceeding the AFRP tendon's tensile strength. Thus, while necessary, prestressing force adjustments alone could not optimize the joint performance effectively.

- **Damper Dimensions**

Given that changes in prestressing force alone were inadequate, the study then focused on modifying the dimensions of the dampers (modifying the leg width from 18mm to 20mm). Dampers play a critical role in energy dissipation and load distribution within the SCPC joints. By adjusting the damper dimensions, it was possible to significantly alter the energy dissipation capacity of the joints. Larger damper leg width was able to dissipate more energy, which is beneficial in reducing the seismic response of the structure. The leg width of 20mm gave about 80% of the energy dissipation of the joint with steel tendon. However, there is a trade-off between energy dissipation and the self-centering ability of the joint. Dampers that are too large may impede the joint's ability to return to its original position after deformation. Through these parametric studies, optimal damper dimensions were identified as a leg width of 20 to 21mm, striking a balance between maximizing energy dissipation and maintaining effective self-centering performance.

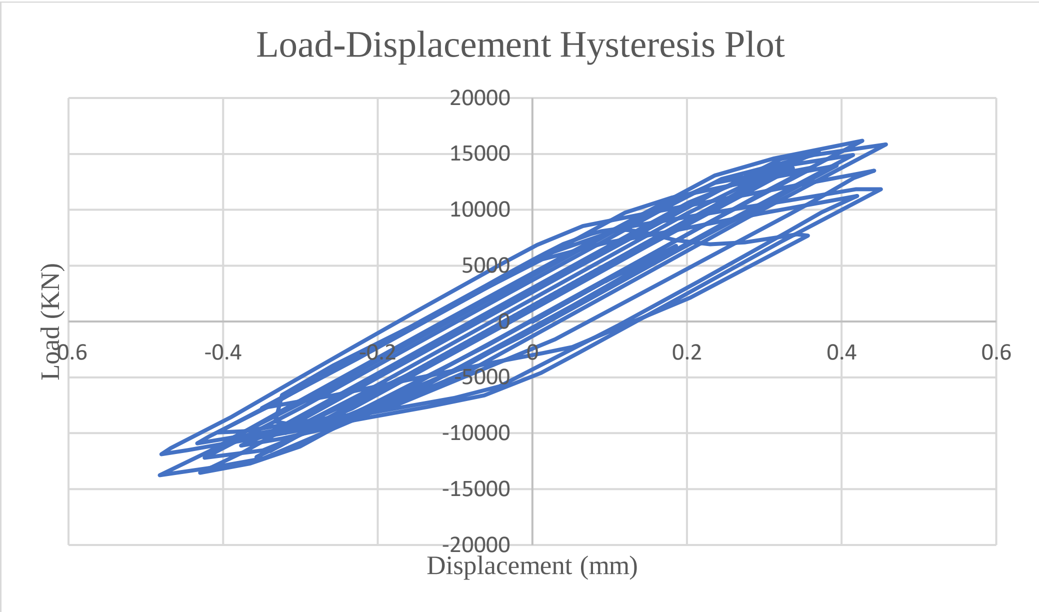

Fig.4.2.3.1 Load vs Displacement Curve

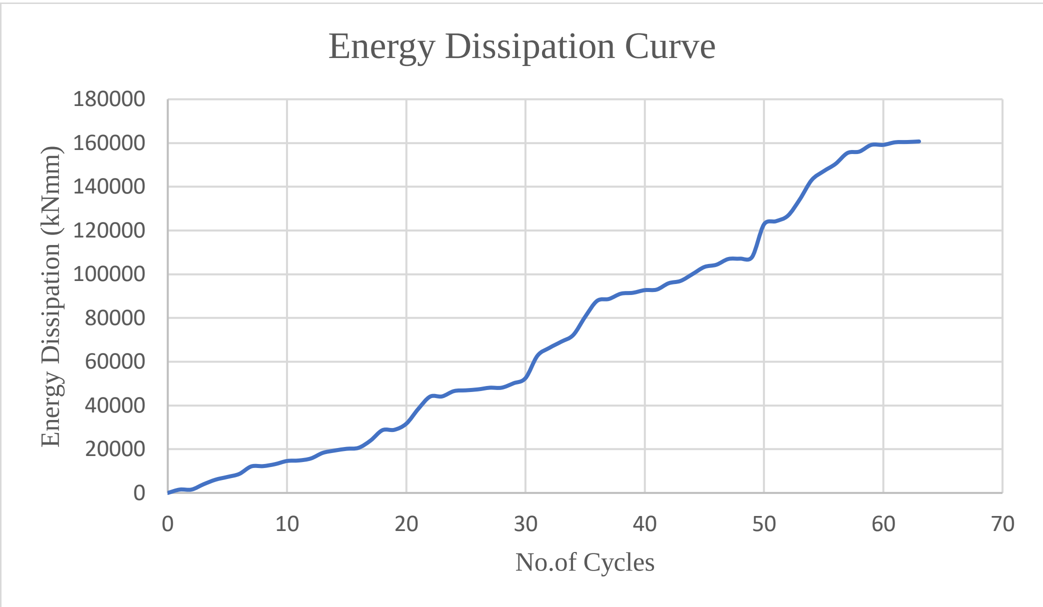

Fig.4.2.3.2 Energy Dissipation Curve

CHAPTER 5
CONCLUSION AND SCOPE FOR FUTURE WORK

5.1 CONCLUSION

This thesis presented an extensive study on the performance of Self-Centering Pre-stressed Concrete (SCPC) joints under cyclic loading, with a specific focus on comparing the use of steel tendons versus Aramid Fiber Reinforced Polymer (AFRP) tendons. The objective was to evaluate and optimize the structural behaviour of SCPC joints to improve their seismic resilience and post-earthquake repairability.

Load-Displacement Behaviour:

- Steel Tendons: SCPC joints with steel tendons exhibited high initial stiffness due to the high modulus of elasticity of steel. The load-displacement curves demonstrated a clear yielding point followed by plastic deformation, which contributed significantly to energy dissipation. However, this plastic deformation led to residual displacements, indicating potential post-earthquake repair requirements.
- AFRP Tendons: The SCPC joints with AFRP tendons showed a comparable initial stiffness but maintained elastic behaviour up to failure. The load-displacement curves remained linear until higher load levels, with minimal residual displacements upon unloading. This demonstrated the superior self-centering capability of AFRP tendons, making them highly desirable for seismic applications due to reduced need for post-earthquake repairs.

Energy Dissipation:

SCPC joints with steel tendons dissipated significant amounts of energy through plastic deformation, which is beneficial for reducing seismic energy transmission. However, AFRP tendons did not dissipate energy through plastic deformation but relied on dampers and other mechanisms. As a result, the overall energy dissipation was lower in AFRP-reinforced joints, highlighting the need for optimizing damper configurations to improve energy absorption.

Parametric Studies and Optimization:

To address the limitations identified with AFRP tendons, parametric studies focused on adjusting prestressing forces and damper dimensions.

- Prestressing Force: It was found that increasing the prestressing force improved initial stiffness and self-centering capabilities but also risked tendon rupture due to the high tensile stresses. Therefore, while prestressing force adjustments are essential, they are not solely sufficient for optimizing joint performance.
- Damper Dimensions: Adjusting damper dimensions significantly impacted energy dissipation and load distribution. Optimal dimensions of 20mm to 21mm leg width of damper were identified to balance energy dissipation and self-centering performance, ensuring that the SCPC joints could effectively absorb seismic energy while maintaining structural integrity and self-centering capabilities.

5.2 FUTURE SCOPE OF WORK

- Investigate the long-term durability of AFRP tendons and SCPC joints under various environmental conditions, including exposure to moisture, temperature fluctuations, UV radiation, and chemical environments.
- Explore alternative methods for applying and maintaining prestressing force in AFRP tendons to enhance initial stiffness and self-centering capabilities without increasing the risk of tendon rupture.
- Study the use of different materials and configurations for dampers within SCPC joints to enhance energy dissipation while maintaining self-centering performance.
- Conduct full-scale cyclic loading tests on SCPC joints with AFRP tendons to validate the findings from small-scale tests and numerical simulations.

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ANNEXURE-IV

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