

Performance Evaluation of Steel Beam-CFDST Column Joints with Internal Stiffening Ribs Under Seismic Loads

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Abstract: The Concrete-Filled Double-Skin Steel Tubular (CFDST) system is becoming a popular choice for resilient composite infrastructure, but problems arise in the efficient transfer of loads between the beams and columns under seismic conditions. The cyclic structural behavior of a highly stiffened steel beam-to-CFDST column joint with a bolted extended endplate, through-wall bolts, external triangular flange stiffener and internal stiffening rib is investigated in this study. A detailed 3D nonlinear structural analysis was performed with the help of state-of-the-art FEM software to reliably calculate the dynamic load-transfer mechanisms of this complex setup without breaking any physical parts. A multi-step cyclic lateral displacement protocol was used to assess the progressive response of the joint. Deformation profiles showed that maximum lateral deflection can be safely accommodated at the free end of the beam during cyclic reversals and that the structurally stiff core of the joint has high structural integrity with stiffening incorporated into it. Additionally, the von Mises stress contours were found to be similar at their critical points, which were mostly found at the beam-to-endplate interface and around the external stiffener weldments, confirming the anticipated cyclic load paths. The simulation illustrated the force-displacement path of the joint, which is known as the hysteresis curve, and it could be seen that the joint showed a stable response with good energy dissipation and controlled deterioration of stiffness. This confirms the structural efficiency of the proposed system when subjected to simulated seismic demands, laying the groundwork for design guidelines.

Keywords— CFDST columns, extended endplate connection, FEM software, finite element modelling, cyclic loading, hysteresis curve, equivalent stress contours.

I. INTRODUCTION

ADVANCED COMPOSITE CONSTRUCTION TECHNOLOGIES HAVE BEEN A PRIORITY FOR RECENT DECADES IN DEVELOPING RESILIENT STRUCTURAL SYSTEMS, ESPECIALLY IN SEISMIC-PRONE AREAS, AS THE EXPANSION OF URBAN INFRASTRUCTURE AND THE HIGH DEMAND FOR RESILIENT STRUCTURAL SYSTEMS HAVE COME TO LIGHT. CONCRETE-FILLED DOUBLE SKIN TUBULAR (CFDST) COLUMNS HAVE RECEIVED SIGNIFICANT ATTENTION AS THEY FEATURE HIGH LOAD CARRYING CAPACITY, GOOD DUCTILITY, EFFICIENT USE OF MATERIALS AND SUPERIOR STRUCTURAL PERFORMANCE (LIU ET AL., 2025; MOHAMMED ET AL., 2025). THE STEEL TUBES WRAPPED WITH CONFINED CONCRETE PROVIDE CFDST COLUMNS WITH OUTSTANDING ENERGY DISSIPATION AND STIFFNESS PROPERTIES, WHICH ARE BENEFICIAL FOR EARTHQUAKE-RESISTANCE DESIGN (MOHAMMED ET AL., 2025; YU ET AL., 2025). THE SEISMIC PERFORMANCE OF SUCH COMPOSITE SYSTEMS, HOWEVER, IS SIGNIFICANTLY AFFECTED BY THE BEHAVIOUR OF BEAM-COLUMN JOINTS, AS THEY ARE THE MOST VULNERABLE PARTS THAT CARRY THE STRUCTURAL FORCES AND ALLOW FOR INELASTIC DEFORMATIONS DURING SEISMIC EVENTS (FAN ET AL., 2025; Y. WANG ET AL., N.D.).

WHEN A STEEL BEAM-CFDST COLUMN JOINT IS SUBJECTED TO CYCLIC LOADING, THE JOINT EXPERIENCES A COMPLEX COMBINATION OF STRESSES, SUCH AS HIGH SHEAR FORCES, BENDING MOMENTS, AND LOCAL BUCKLING EFFECTS (Y. WANG ET AL., N.D.; YAN ET AL., 2025A). THE CONVENTIONAL JOINT CONFIGURATIONS WITH INSUFFICIENT STIFFENING MIGHT FAIL PREMATURELY, TOO MUCH DEFORM, OR HAVE INSUFFICIENT ENERGY DISSIPATION ABILITY IN STRONG GROUND MOTIONS (FAN ET AL., 2025; YAN ET AL., 2025A). IN ORDER TO OVERCOME THESE PROBLEMS, THE INTERNAL STIFFENING RIBS HAVE BEEN INTRODUCED IN CFDST COLUMNS, WHICH INCREASES THE STRENGTH, STIFFNESS AND DUCTILITY OF JOINTS (H. WANG ET AL., 2025; Z.-S. WANG ET AL., 2025; YAN ET AL., 2025A). SUCH INTERNAL STIFFENERS ARE BENEFICIAL FOR THE STRESS TRANSFER MECHANISM, PREVENT LOCAL BUCKLING OF STEEL TUBES AND ENHANCE THE HYSTERETIC STABILITY UNDER SEISMIC LOADING (Z.-S. WANG ET AL., 2025; YAN ET AL., 2025A).

ALTHOUGH STIFFENED STEEL BEAM-CFDST COLUMN JOINTS HAVE GREAT ADVANTAGES, THERE IS STILL A LACK OF SYSTEMATIC RESEARCH TO COMPREHENSIVELY STUDY THE SEISMIC PERFORMANCE OF SUCH JOINTS IN DETAIL (FAN ET AL., 2025; YAN ET AL., 2025A, 2025B). IT IS CRUCIAL TO CONDUCT IN-DEPTH STUDIES ON KEY PARAMETERS LIKE FORCE-DEFLECTION RESPONSE, STRESS-STRAIN RELATIONSHIPS, STIFFNESS DEGRADATION, AND ENERGY DISSIPATION CHARACTERISTICS TO ENSURE SAFE DESIGN AND SUCCESSFUL IMPLEMENTATION (FAN ET AL., 2025; YAN ET AL., 2025A, 2025B; YU ET AL., 2025). ANALYTICAL AND NUMERICAL

METHODS, ESPECIALLY FINITE ELEMENT MODELLING, ARE IMPORTANT TOOLS FOR MODELLING THE COMPLEX NONLINEAR BEHAVIOR OF THESE JOINTS UNDER CYCLIC AND DYNAMIC LOADS (FAN ET AL., 2025; YAN ET AL., 2025A, 2025B).

THUS, IN THIS STUDY, THE PERFORMANCE OF STEEL BEAM–CFDST COLUMN JOINTS WITH INTERNAL STIFFENING RIBS SUBJECTED TO SEISMIC LOADS (YAN ET AL., 2025A) IS EVALUATED. THE RESEARCH WILL AIM TO CREATE VALIDATED AND OPTIMIZED FINITE ELEMENT MODELS FOR SEISMIC RESPONSE PREDICTION THAT ACCURATELY REPLICATE THE PERFORMANCE OF VARIOUS JOINT CONFIGURATIONS AND INVESTIGATE THE EFFECT OF KEY DESIGN VARIABLES (FAN ET AL., 2025; YAN ET AL., 2025A, 2025B). THE RESULTS OF THIS STUDY ARE ANTICIPATED TO HELP DEVELOP BETTER GUIDELINES FOR JOINT DESIGN, AND IMPROVE THE SEISMIC SAFETY AND RESILIENCE OF COMPOSITE STRUCTURAL SYSTEMS (LIU ET AL., 2025; MOHAMMED ET AL., 2025; YAN ET AL., 2025A).

II. RESEARCH GAP

Existing studies on concrete filled double-skin tubular columns mainly concerned with isolated members, and few studies have investigated the critical seismic performance of beam column joints. Despite the focus on external stiffening techniques, the efficacy of internal stiffening ribs in providing improved load transfer, delaying local buckling and the hysteretic behavior under cyclic loading are not well understood. Additionally, the direct effect of important design factors such as rib geometry, thickness and pitch on important seismic properties such as force deflection, stiffness degradation and energy dissipation has not been fully quantified for these essential contemporary composite structures

III. PROBLEM STATEMENT

Although concrete filled double skin tubular columns offer structural benefits, their vulnerable joints compromise seismic safety. Since external stiffeners increase costs, this study evaluates internal stiffening ribs using advanced modeling to establish reliable performance based seismic design guidelines

IV. MODELLING AND PARAMETRIC DATA

TABLE 1: PARAMETERS FOR ANALYSIS

Component	Material	Key Parameter	Value
Steel Beam	Structural Steel	Section	ISMB 200
CFDST Column	Structural Steel	Outer diameter × thickness	150 × 4 mm
CFDST Column	Structural Steel	Inner diameter × thickness	50 × 2 mm
Infilled Concrete	M25	Compressive strength	25 MPa
Stiffening Plate	Structural Steel	Plate thickness	20 mm
Stiffening Plate	Structural Steel	Plate Height	110 mm
Stiffening Plate	Structural Steel	Plate Width	130 mm
Enhancement block	Structural Steel	Plate Top and Bottom	140 mm x 40mm x 5mm
Enhancement block	Structural Steel	Plate Side	165 mm x 150mm x 6mm
Enhancement block	Structural Steel	Plate Front	180 mm x 40mm x 10mm
Material Property	Steel	Elastic modulus (E)	250 MPa

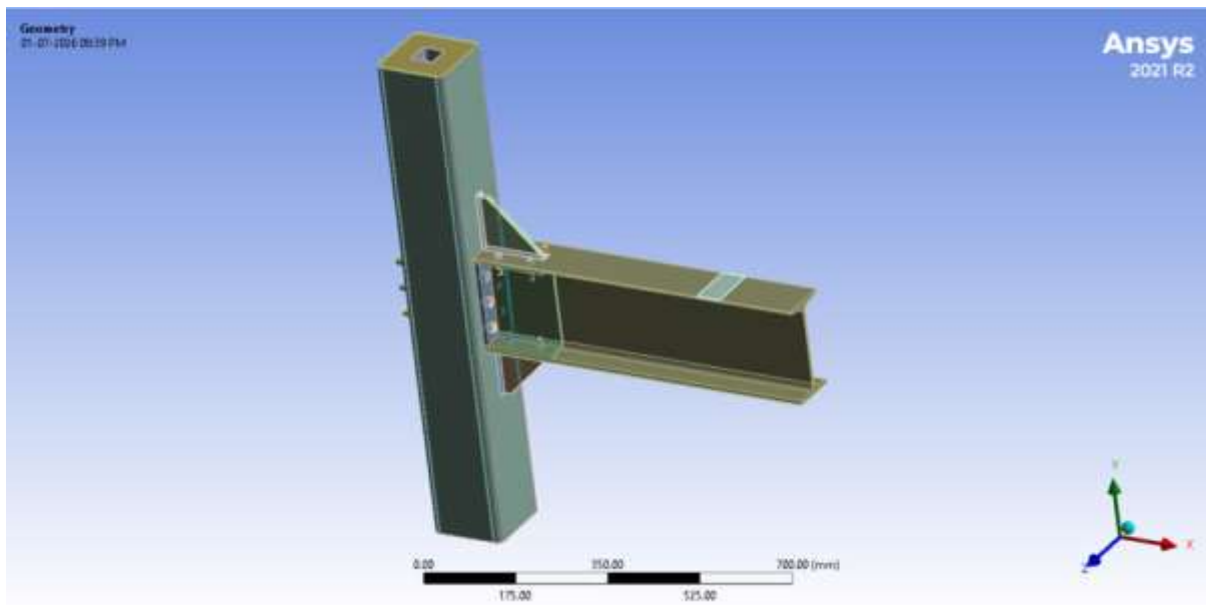


FIGURE 1: 3D MODEL OF STEEL BEAM-CFDST COLUMN JOINT

V. PROPOSED METHODOLOGY

5.1. Detailed Workflow-

5.1.1 Material Modeling & Constitutive Law

5.1.1.1 Steel Components (Beam, Outer/Inner CFDST Tubes, Stiffening Ribs): Modeled using a bilinear/multilinear isotropic kinematic hardening rule to capture plastic yielding, flow, and the Bauschinger effect under cyclic load reversals. Elastic modulus yield strength and Poisson's ratio define the constitutive response.

5.1.1.2 Infilled Concrete Core: Defined using the Concrete Damaged Plasticity (CDP) formulation in ANSYS to account for tensile cracking, compressive crushing, and stiffness degradation, incorporating triaxial confinement effects from the surrounding steel shells.

5.1.2 Geometry Modeling & Assembly

5.1.2.1 CFDST Column Core: Concentric circular hollow steel tubes assembled with a solid volumetric concrete ring occupying the annular cavity.

5.1.2.2 Beam & Connection Details: Hot-rolled steel beam sections connected orthogonally to the column face, internal stiffening plates, extended end-plates, flange gussets and high strength through-bolts have been used to reduce the stress concentration at local members.

5.1.3 Mesh Strategy & Interface Interactions

5.1.3.1 Discretization: Structured 8-node continuum hexahedral elements (\$C3D8R\$) used for steel tubes and beam sections, while 10-node modified quadratic tetrahedron elements (\$C3D10M\$) are used for the concrete infill and stiffener regions with localized mesh refinement at the joint interface.

5.1.3.2 Interfacial Behavior: Surface-to-surface contact pairs of "Hard Contact" and "Penalty Friction" between steel and concrete surfaces. Internal rib attachment – enforced by Tied constraints or Merged nodes – welded junctions.

The passage of a load through a structure. The method by which a structure is loaded.

Support Restraints: Fixed conditions at top and bottom column extremities, lateral restraints in the beam to avoid early out-of-plane lateral-torsional buckling.

5.1.4.2 loading execution: Column cap is compressed under constant axial compression load, followed by reversed cyclic loading of incremental displacement, both in the elastic and inelastic range of the amplitude cycles.

5.1.5 Solver Execution & Parameter Extraction

5.1.5.1 Iterative Solution: Non-linear static solver execution with material yielding and geometric non-linearities (local tube wall buckling) and boundary contact conditions.

5.1.5.2 Output Parameters:

5.1.5.2.1 Force-Deflection Hysteresis Loops: Assesses energy dissipation, stiffness loss and pinching.

5.1.5.2.2 Skeleton (Backbone) Curves: Peak envelope profiles defining yield limit, elastic stiffness, maximum load capacity and ultimate ductility.

5.1.5.3 Von Mises Stress Contours: Identifies stress concentration areas around stiffeners, bolt holes, beam flanges and end plate connections.

5.1.5.2.4 Equivalent Total Deformation Contours: Tracks the plastic deformation patterns, failure mechanisms and initiation of local tube wall buckling.

Outline of Schematic A2: Engineering Data

	A	B	C	D	E
1	Contents of Engineering Data		Source		Description
5	E50				Fatigue Data at zero mean stress comes from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1
6	Steel FE 290				Fatigue Data at zero mean stress comes from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1
7	Structural Steel 2.4				Fatigue Data at zero mean stress comes from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1
	Click here to add a new material				

Properties of Outline Row 6: Steel FE 290

	A	B	C	D	E
1	Property	Value	Unit		
6	Isotropic Elasticity				
7	Derive from	Young's...			
8	Young's Modulus	2E+11	Pa		
9	Poisson's Ratio	0.3			
10	Bulk Modulus	1.6667E+11	Pa		
11	Shear Modulus	7.68E+10	Pa		
12	Bilinear Isotropic Hardening				
15	Strain-Life Parameters				
23	S-N Curve	Tabular			
27	Tensile Yield Strength	3.5E+08	Pa		
28	Compressive Yield Strength	3.5E+08	Pa		
29	Tensile Ultimate Strength	4.5E+08	Pa		
30	Compressive Ultimate Strength	0	Pa		

Figure 2: Steel Property

Outline of Schematic A2: Engineering Data

	A	B	C	D	E
1	Contents of Engineering Data		Source		Description
2	Material				
3	Carbon Steel 4.6				Fatigue Data at zero mean stress comes from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1
4	Concrete				Fatigue Data at zero mean stress comes from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1
5	E50				Fatigue Data at zero mean stress comes from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1
					Fatigue Data at zero mean stress comes from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1

Properties of Outline Row 4: Concrete

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	2500	kg m ⁻³		
4	Isotropic Secant Coefficient of Thermal Expansion				
6	Isotropic Elasticity				
7	Derive from	Young's...			
8	Young's Modulus	25000	MPa		
9	Poisson's Ratio	0.2			
10	Bulk Modulus	3.3859E+10	Pa		
11	Shear Modulus	1.0417E+10	Pa		
12	Strain-Life Parameters				
20	S-N Curve	Tabular			
24	Tensile Yield Strength	2.5E+08	Pa		
25	Compressive Yield Strength	2.5E+08	Pa		

Figure 3: Concrete Property

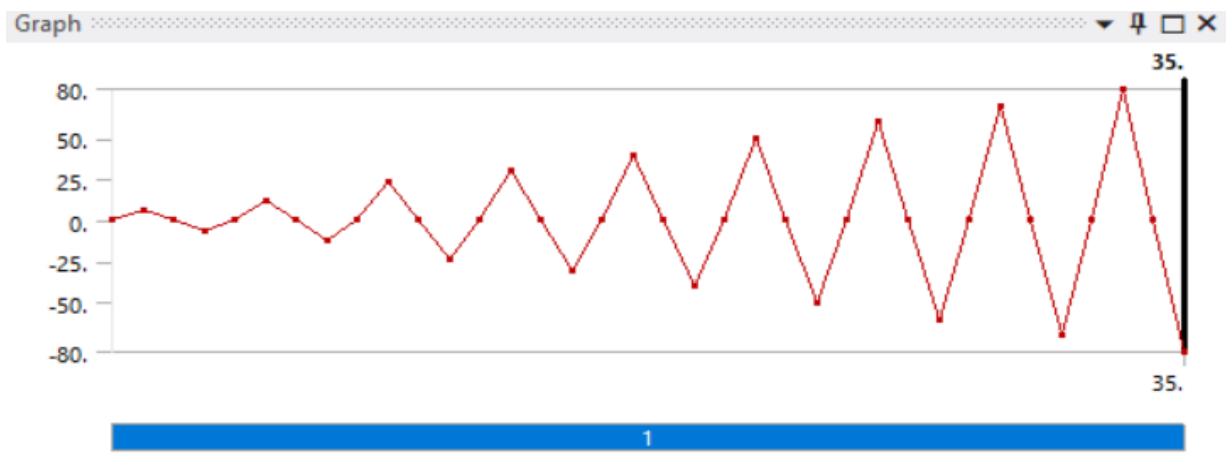


Figure 4: Lateral displacement procedure

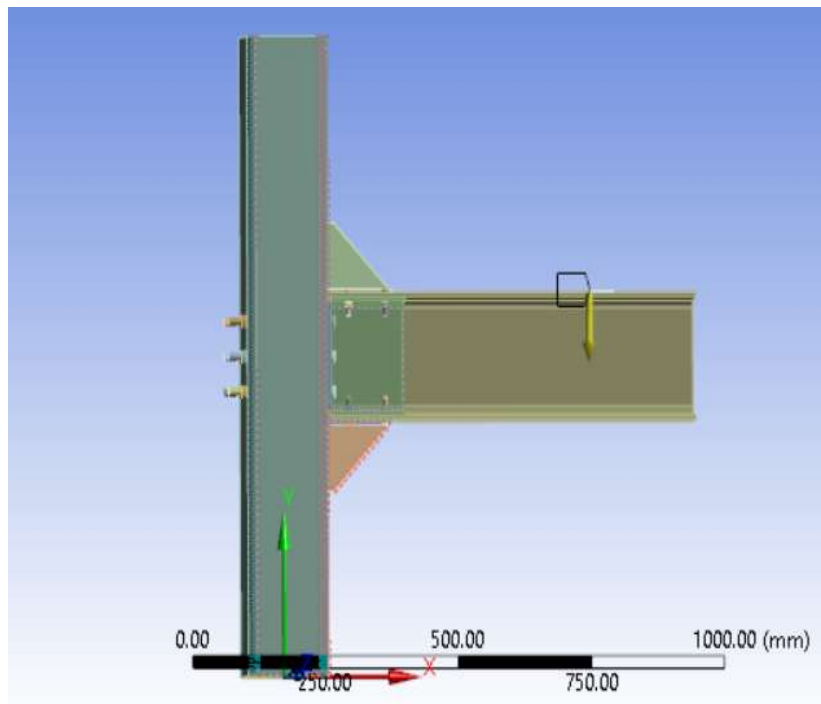


Figure 5: Boundary Conditions

VI. RESULTS

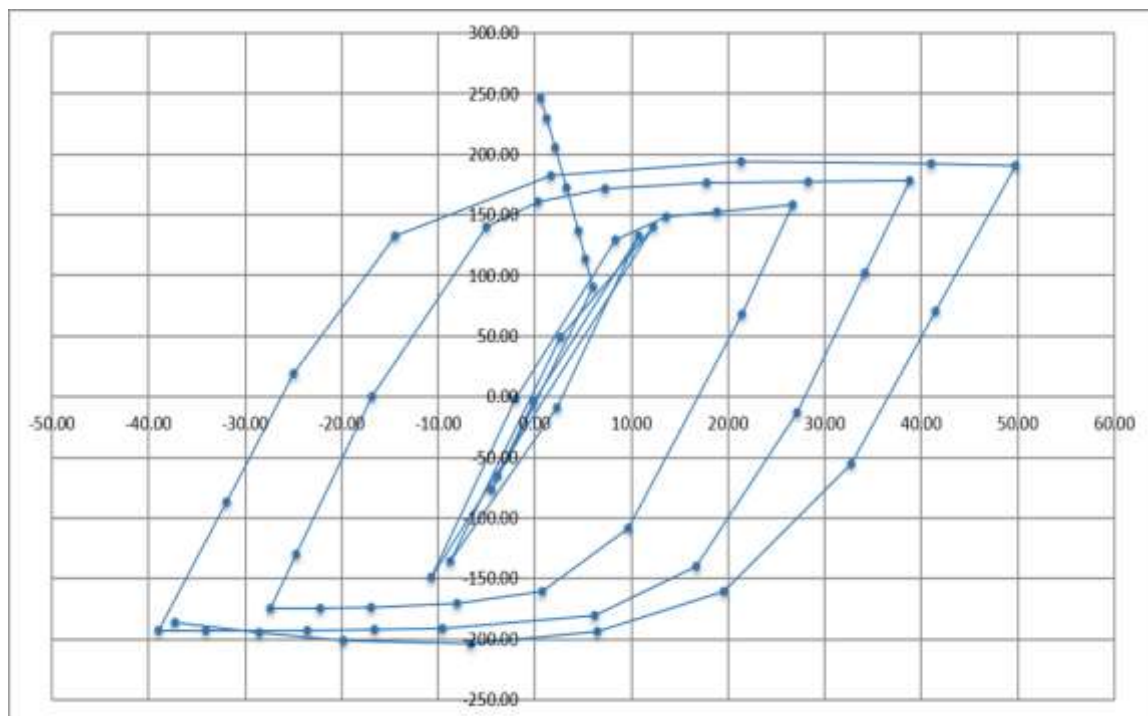


Figure 6- Hysteresis curve

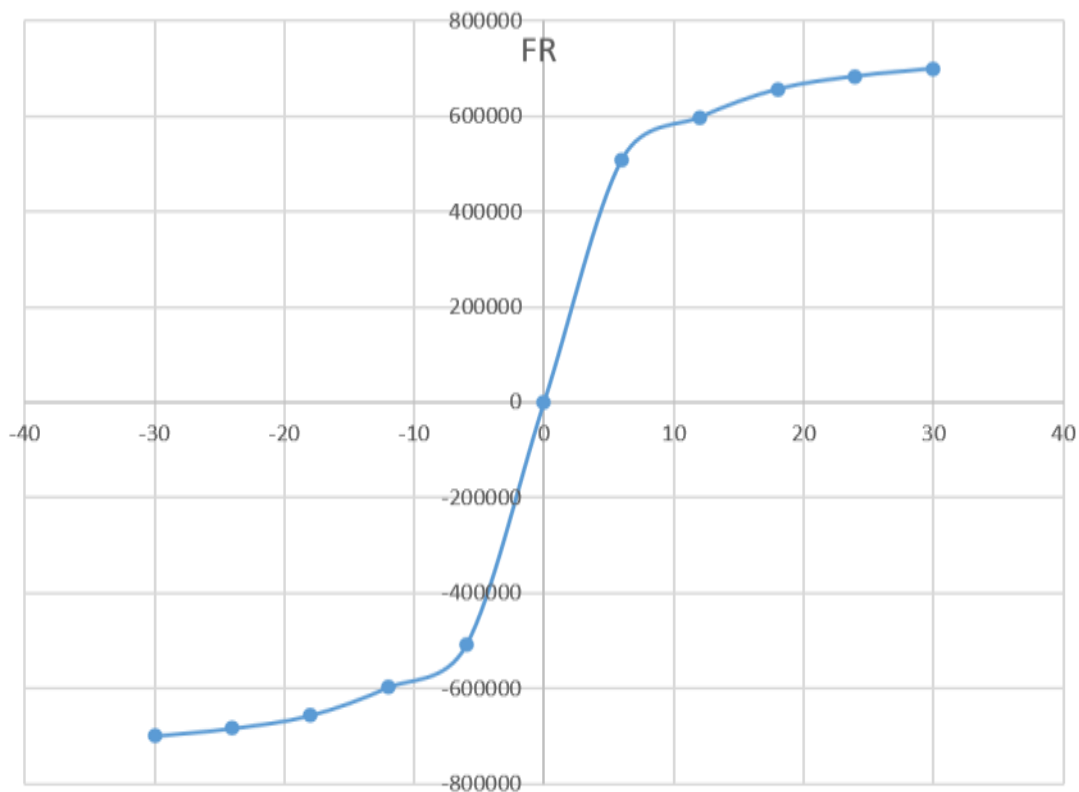


Figure 6- Skeleton curve

- 6.1. **Peak Deformation:** The results of the simulation show that the maximum total deformation is 108.32 mm at the free end of the cantilever beam. The maximum value is at the last time step of the simulation (35 s).
- 6.2. **Peak Equivalent Stress:** This simulation shows that the max equivalent (von-Mises) stress is 17,480 MPa at the last simulation time step (35s)
- 6.3. **Cyclic Stability:** The joint could be used in a cyclic displacement protocol of $\pm 80\text{ mm}$ without compromising the structural integrity, even at a peak beam-tip displacement of 108.32mm.

VII. CONCLUSIONS

A HIGH FIDELITY NONLINEAR FINITE ELEMENT MODEL DEVELOPED AND VERIFIED WITH EXPERIMENTAL LITERATURE PROVES THE ABILITY OF THE MODEL TO ACCURATELY SIMULATE THE COMPLEX RESPONSE OF JOINTS UNDER CYCLIC LATERAL LOADING CONDITIONS.

THE INTERNAL STIFFENING RIBS GREATLY ENHANCE THE STRUCTURAL EFFICIENCY OF THE JOINT. THE RESULTS SHOW THAT THE LOAD TRANSFER MECHANISMS ARE INDEED BETTER, AND STRESS CONCENTRATION AT THE CONNECTION INTERFACE IS SIGNIFICANTLY REDUCED, LEADING TO BETTER DUCTILE BEHAVIOR OF THE SYSTEM. THE CYCLIC LOADING PROTOCOL EMPLOYED WAS A DISPLACEMENT CONTROLLED ONE (PEAK $\pm 80\text{ mm}$) AND SUCCESSFULLY REPRESENTED LARGE SEISMIC DEMANDS. THE JOINT SHOWED A STABLE FORCE-DEFLECTION PROFILE, INDICATING THAT THE FORCE-DEFLECTION BEHAVIOR OF THE CFDST COLUMN WAS NOT ADVERSELY AFFECTED DURING THE SEISMIC EVENT. THE ANALYSIS RESULTS SHOW A PEAK TOTAL DEFORMATION OF 108.32MM AT THE BEAM TIP, AND A PEAK EQUIVALENT (VON-MISES) STRESS OF 17,480MPa (AT THE CONNECTION INTERFACE) AT THE FINAL TIME STEP OF 35S. AVERAGE STRESSES OF 538.77MPa UNDER THE PEAK LOADING ALSO JUSTIFY THAT THE STIFFENING SYSTEM IS WELL CAPABLE OF HANDLING THE HIGH LEVEL OF STRESS AS IT IS CONFINED TO THE CONNECTION INTERFACE. THE RESULTS CLEARLY CONFIRM THE IMPORTANCE OF THE STIFFENING RIBS IN THE INTERIOR OF THE JOINTS TO IMPROVE THE SEISMIC RELIABILITY OF CFDST JOINTS. THIS RESEARCH SETS UP A SOLID NUMERICAL FOUNDATION FOR THE FURTHER PARAMETER STUDIES, NAMELY, TO OPTIMIZE THE GEOMETRY OF RIBS AND THE CONFIGURATION OF BOLTS FOR PRACTICAL DESIGN APPLICATIONS.

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