Computational study of the effect of welding on load carrying capacity of Warren truss

Murali S[1], Dr. Chethan K[2], Dr. Achutha Herur Gopalaiah[3]

[1]M. Tech (Structural Engineering) student, Dept of Civil Engineering, UVCE, Bengaluru, Karnataka, India
[2] Associate Professor, Dept. of Civil Engineering, UVCE, Bengaluru, Karnataka, India
[3] Sr. Manager PO/PMO, ESI Software India Pvt. Ltd., Bengaluru, Karnataka, India

---***---

Abstract - *There are the challenges associated with welding, which includes development of residual stresses and distortions that can compromise structural stability and increase failure risks in the truss. This study utilizes computational simulations to analyze the effects of welding parameters on the behavior of trusses. The simulations are conducted using Visual-Weld (CSM) with arc welding as the primary joining technique. The investigation focuses on the influence of welding-induced residual stresses, heat-affected zone (HAZ) characteristics, and geometric distortions on the overall performance of the Warren truss. Advanced finite element method tools are used to serve the above purpose. The study progressed with the design of the weld, bead and trajectory creation, material and weld input calibrations. Then the thermal, metallurgical and mechanical analysis is carried out. The weld effect on the load carrying capacity of warren truss is assessed in terms of determining the displacement due to effect of loading alone and displacement due to combined loading and welding. The result shows the significant effect of welding on the Warren truss's load carrying capacity.*

***Key Words*: Heat-affected zone, Warren truss, Thermal analysis, residual stress, distortion, Mechanical analysis, Visual-Weld (CSM).**

1.INTRODUCTION

Trusses are more popular and very often used type of steel structure. Truss consists of triangulated system of interconnected, straight structural elements of tension and compression members. Members of trusses are acted upon with axial loads applied only at the joints. Trusses can be designed with connections of either simple bolted or welded connections for all types of member sections. Trusses are widely used in bridges, buildings, towers, and industrial frameworks due to their high strength-to-weight ratio. Trusses are classified based on geometry, load conditions, load distribution, and material composition. Warren Truss comprises of equilateral triangles, ensuring even load distribution. Welding provides complete freedom of design to structural engineers as well as architects. Properly welded joints are stronger than bolted joint. Some of the common weld defects include lack of fusion, porosity, cracking, distortions and undercut. The different weld parameters are considered.

1.1 Welding Parameters

Travel speed is the speed at which the electrode moves along the weld joint. It is also known as the Weld Velocity. It is usually represented as the mm/min. Optimum weld speed provides uniform penetration and controlled bead size. Heat input affects weld microstructure, Heat affected zone and mechanical properties. Heat input is the amount of heat energy delivered to the material during welding. Optimum heat input creates balanced microstructure and controlled stress. Weld penetration refers to the depth to which the weld metal (filler material) and base metal (workpiece) fuse together during the welding process. To ensure the proper bonding between the materials, and to expect materials to handle mechanical loads and stresses, it is important to have the proper specified and complete penetration. Welding current determines the heat input to the weld joint, affecting penetration and deposition rate. Optimum weld current provides proper penetration, bead profile and good fusion with base metal. Arc voltage is the potential difference between the electrode and the workpiece, measured in volts (V). Optimum arc voltage provides stable arc, proper bead width and reduced defects.

1.2 Visual-Weld (CSM) Software

Visual-Weld is a Computer-Aided Engineering (CAE) software specifically designed for welded structure analysis. It is a module of Visual-Environment, developed by ESI Group, and is commonly used for weld simulations in structural and manufacturing industries. It integrates advanced finite element analysis (FEA) with welding process simulations, helps to study thermal, mechanical and metallurgical effects of welding. Visual-Weld (CSM) provides a wide range of features for welding process simulation and analysis. The primary capability of the software includes Weld modelling and Simulation, Heat source modelling and Thermal Analysis (Temperature distribution, Cooling rate, and Heat-affected zones (HAZ). Structural and residual stress analysis can be carried out using the Visual-Weld (CSM) software. The software also provides the provision for the Material and Metallurgical analysis and phase Transformation modelling by incorporating the weld metal properties. Benefits of Using Visual-Weld (CSM) is accurate welding simulation, reduces physical testing costs, predicts residual stresses, prevents weld failures, optimizes welding parameters, improves productivity, reduces distortion, minimizes post-weld corrections.

1.3 Finite element analysis

Finite element analysis is a powerful computational technique used to solve complex engineering problems involving structures, heat transfer, fluid dynamics, and many more. By breaking down a larger system into smaller, simpler parts (finite elements), FEA enables us to analyse the behaviour of materials and components under various conditions, such as load, temperature, or pressure. The steps to be followed in FE analysis is discretization, meshing, developing governing equations, element formulation, input boundary condition, obtain solution and post-processing.

2. LITERATURE REVIEW

Manik, et al. (2012) investigated to know the mechanical properties of the cast iron and mild steel before and after the welding. The metals with any cross sections that have undergone the Heat treatment shown the result that the stress will be reduced after welding compared to that without the heat treatment. Also, result is evidential that hardness after welding is increased if carried out the rapid cooling. The experimentations carried out by the Authors suggested that the proportional limit of the workpiece is reduced due to the welding effect, strength also reduced, but the hardness was increased. Hence authors concludes that there is significant change in the properties of the metals because of welding imposed on it.

Van Nhat Nguyen, et al. (2016) carried out Computational simulation welding with the help of Finite element Method and predicted the residual stresses and strains. They carried out Thermal, Metallurgical and Mechanical Analysis post welding. Authors used Visual-Weld software for the simulation and Analysis of T-Joint and the results of Deformation, Hardness, phase transformation were tabulated. Authors indicated that Heat energy affects penetration depth of seam weld. Authors suggests using proper weld materials, to have good weld gap and to make the proper surface clean before proceeding with the process of welding.

Tadano Satoshi, et al. (2019) investigated on the steel angle sections of the trusses and the deformation that the angle section takes place due to the welding processes. The Authors analysed and evaluated welding deformation using both Joint model as well as the real-scale Truss structure model. The Authors provides the result after the study that the main beam of welded truss structure was seen to be arched against the direction of angular distortions. They used uniformly distributed Inherent strain theory within the Mechanically melting zones. The Authors also studied the theoretical ways in which the welding deformation in the Truss structure could be reduced.

Okonkwo V O, et al. (2021) investigated on the different trusses and determined the effect of secondary stresses on the final weight of the structure. They made the comparison between the pin-jointed and rigid jointed trusses. Authors after the study are in the Favour of the Rigid-Jointed trusses and suggests that the Rigidly jointed (welded) trusses require lighter and cheaper structures than pin-jointed trusses. Welded Joints when made comparison with the pin joints, former's load carrying capacity is substantially increased in comparison with the later.

Mohamed M. Ali and Moatasem M. Kh (2020) investigated on the effect of the welding parameters on the mechanic properties of the steel weldment. To know the effect caused by different welding parameters, the following parameters were considered: Welding speed, Plate thickness, Type of arc welding, Type of electrode and welding current. The result of the study suggested that as the heat input increases, the weld speed reduces, but the weld current increases, and thereby, it is effective for large plate thickness. The Authors observed change in the phase at the Heat affected zone root. They are in the opinion that weld electrode also has the influence on the efficiency of the welding process. The Authors also suggests the welding input for better weld results.

Dengyiding Jin, et al. (2021) investigated on the effect of the welding on the stiffness and strength of the CFST (Concrete-filled steel tubular) K and Y-Joint. The Authors used the Advanced FEM tools for the achievement of the above purpose. The test data were collected by the authors and are used for validation. To facilitate the simulation of Welding heat generation, as well as the Residual stress so obtained due to welding. The study carried out by the authors suggested that Brace to Chord ratio is the important governing factor in the Joint failure. Authors hinted the result that when the weld leg thickness is reduced, it moderately reduces the joint strength and stiffness, but indeed smaller and lower region of residual stress is induced.

3. METHODOLOGY

The Methodology followed in the study are as follows:

(i) Defining the project and its objectives, identify the key factors affecting the load-carrying capacity of welded trusses, such as welding parameters, heat-affected zones (HAZ) and residual stresses.

(ii) Prepare the Truss model required to carry out simulations using the Visual-Mesh Software. Mesh the model, cleanup and carry out suitable checks on mesh quality.

(iii) Create weld trajectory, weld load, material property calibration, and assign material to parts.

(iv) Making Weld simulation setup by inputting Weld parameters, initial ambient temperature, Clamping conditions, Load and weld sequence.

(v) Run the simulation to get the Normal Termination of both Thermo-Metallurgical and Mechanical Analysis.

(vi) Evaluate the Residual stresses and deformations results.
(vii) Assess the effect of welding of different types of Trusses by examining the iterations with and without loading it.

(viii) Tabulation of the results obtained.

(ix) Make discussions over the results obtained and giving the conclusions of the work carried out.

The flowchart of the methodology followed in the work is represented in the Fig- 1.

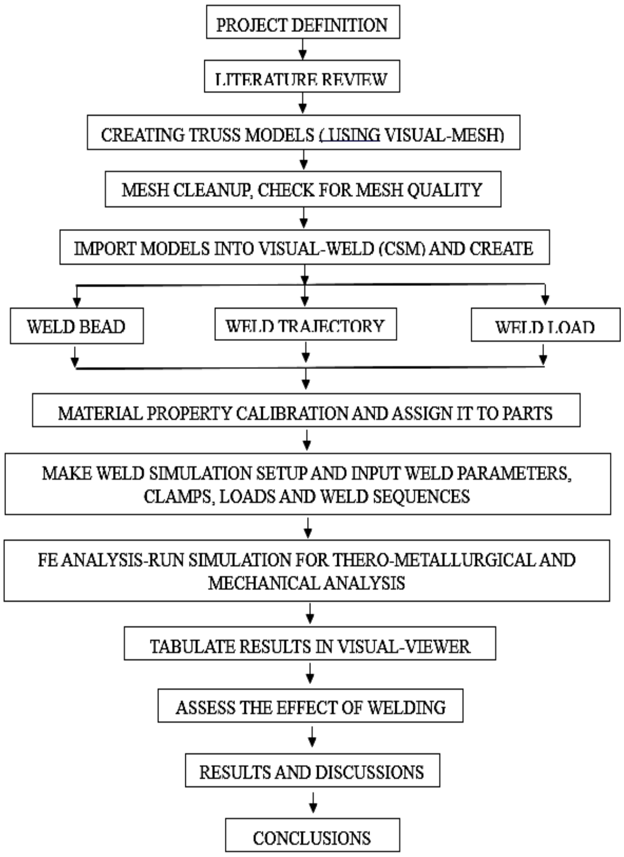

Fig -1: Flowchart of the methodology

4. WORK DONE

The CAD drawing of the Truss is prepared in the Visual-Mesh software by properly taking into consideration the dimensions. Each member is stored as the parts, now each part is meshed in the Visual- Mesh software.

Once after the model is meshed, then it is carried out with suitable checks for mesh quality. The Arc welding is used to connect the members of the Trusses at joints. The weld design is done, and suitable checks are carried out.

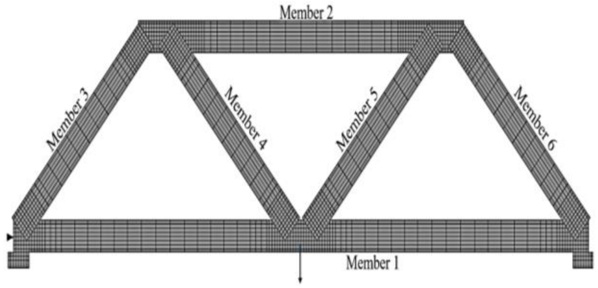

Fig -2: Warren truss modeled in the software and considered for the study

The Material properties of the steel used in the FE analysis are tabulated as below in Table -1. These properties listed are at the ambient temperature, before the start of the welding process.

Table -1: Material properties

Material Property	Value	Units
Modulus of elasticity	2.1 x 10^8	kN/m^2
Poisson's ratio	0.3	-
Density	78.2	kN/m^3

The details of the Warren truss model are listed out in the Table -2

Table -2: Details of Truss Model

Sectional designation of Truss members	ISA 80X80
Size of Truss members	80mm X 80mm
Thickness of Truss member	8mm
Sectional area of Truss members	$1221mm^2$
Weight per meter of Truss members	9.6kg
Weld dimension	5mm X 5mm
Base dimension	120mm X 80mm X 40mm

The details of the weld parameters provided and the minimum required value to be provided are given in the Table -3

Table -3: Design of the weld

Sl no	Parameters	Provided	Minimum required
1	Fillet weld size (mm)	5	4.462
2	Length of weld (mm)	323.428	288.6586
3	Design strength (N/mm^2)	189.37	131.197

Once the design of the weld and providing the weld parameters are done, the checks for whether given welded joint is sufficient to safely carry the applied load or not is done. The weld strength was found to be sufficient and joint strength also found to be sufficient to carry the load applied on the truss.

As per the IS 800 and AWS D1.1 codal provisions, the design of the weld is carried out. For the given weld, angular distortion induced is estimated.

For Warren truss:

Provided Energy input is q = 600 J/mm

Angular distortion in fillet weld, $\theta = \frac{5*q}{E*t}$

Where t is the plate thickness

$$\theta = \frac{5*600}{210000*8}$$

$\theta = 0.0017857$ radians

Hence, Angular distortion in fillet weld is

$\theta = 0.1023^0$

According to AWS D1.1:2000 the allowable angular distortion for structural welding ≤ 1^0 and allowable angular distortion for precise structures with tight tolerance ≤ 0.5^0.

As angular distortion is less than these limits, it is safe.

As per the design of the weld, the minimum required weld thickness and minimum length of the weld is provided, to get proper weldment.

Weld bead and weld trajectories are created. Weld trajectory denotes the path in which the welding is proceeded. The poisson's ratio is unaffected with the increase in the temperature and the value of Poisson's ratio for the steel is taken as 0.3, independent of temperature. The Young's Modulus and density varies with the temperature. Then the material calibration is done.

The calibration of Weld input such as penetration, length of Arc weld, width of Arc weld etc. are done, for the purpose of achieving the good quality weld. For this purpose, a joint of the model is considered, welding inputs are altered until the normal termination of the Thermo-Metallurgical and Mechanical process takes place. After Normal termination, cross check for sufficient heat input penetration is done.

Clamping is created. Clamping holds the workpieces in the correct position while the welding takes place. Clamping provides the accurate alignment of workpieces, improves weld quality, distortion and warping will be prevented, safety and stability is increased. Clamps must be provided at the places where there would be more distortions during the process of welding. The proper sequence is followed during the providing of clamping as well as during the removal of the clamping.

Thermal and mechanical contacts are defined.

The simulation setup is done. The simulation details are presented in the Table -4

Table -4: Simulation details

Sl no	Parameters (units)		Value
1	Energy/unit length (J/mm)		600
2	Length of Arc(mm)		9
3	Width of Arc (mm)		8
4	Penetration (mm)		3.53
5	Weld speed (mm/s)		7
6	Efficiency		1
7	Power ratio		1.2
8	Length ratio		0.5
9	Ambient temperature(^{0}C)		20
10	Load (kg)	Case 1	10000
		Case 2	15000

The simulation setup includes project description and material assignment, process chaining, definition of welds, clamping system, heat exchange condition, loading condition, contact and connection condition and sequence manager.

After the simulation setup is ready, mechanical displacement analysis and mechanical von-mises residual stress analysis is carried out.

Mechanical displacement analysis is the study of the deformation or movement of the welded materials during and after the welding process. This analysis is crucial for understanding how the application of heat, the fusion of materials, and the cooling rates affect the geometry.

Thermal expansion and contraction play an important role in mechanical displacements during welding. When the material is heated in the welding process, it expands, and when it cools, it contracts. The heat-affected zone (HAZ), weld bead, and base material all experience different temperatures and cooling rates, leading to differential expansion and contraction.

Cooling rate is faster in the weld metal compared to the base metal, this thermal mismatch can create residual stresses in different regions, especially in the regions of heat-affected zone (HAZ).

5. RESULTS

To assess the effect of welding on the Load carrying capacity of different members of the truss, the displacements (both vertical and lateral displacements) are measured at the different nodes of the warren truss. It is because the force and displacements are directly related to each other.

The truss members are measured for the displacement before loading which indicates the displacement induced in the members because of welding. Also, the truss members are measured for displacements at different nodes after loading which indicates the displacement induced in the members due to the combined effect of Welding and loading. Hence this analysis provides the effect that welding is inducing on the different members of the Warren Truss.

The curves to show the effect of welding are plotted. The curve of 'Before clamp release' indicates the displacements in the members due to the localized residual stresses present after welding. It is the minor displacements present in the members.

The curve of 'Clamp released' indicates the displacements at the different nodes in the member purely because of welding.

The curve of 'Loaded' indicates the displacements at the different nodes in the member due to the combined effect of welding and loading.

For the Warren truss, the results shows that there is both positive and negative effect of welding in the different members of the warren truss.

Both the vertical displacement and the lateral displacement due to the loading and welding are plotted for both horizontal and diagonal members.

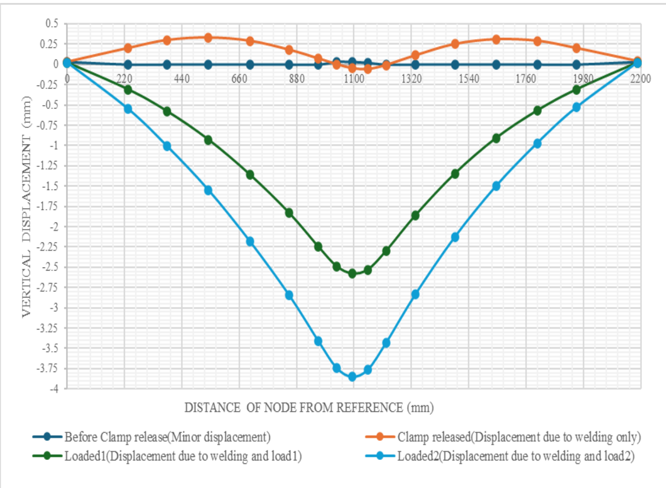

Chart -1: Vertical displacement in horizontal base member (member 1)

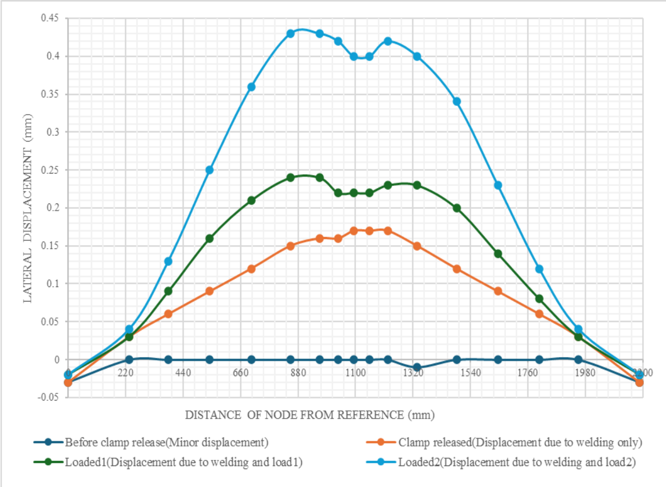

Chart -2: Lateral displacement in horizontal base member (member 1)

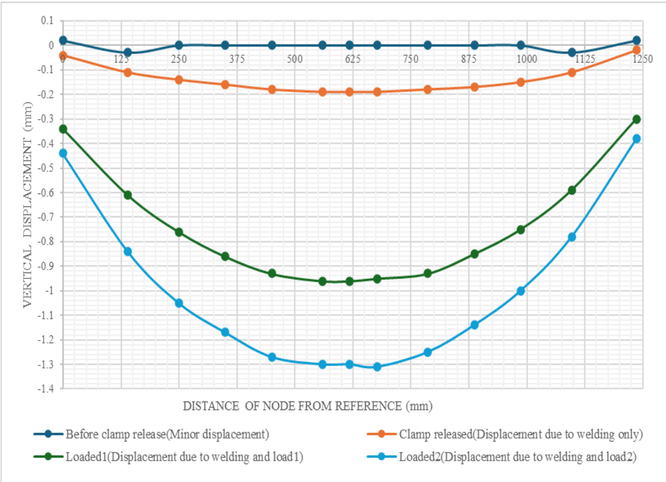

Chart -3: Vertical displacement in horizontal top member (member 2)

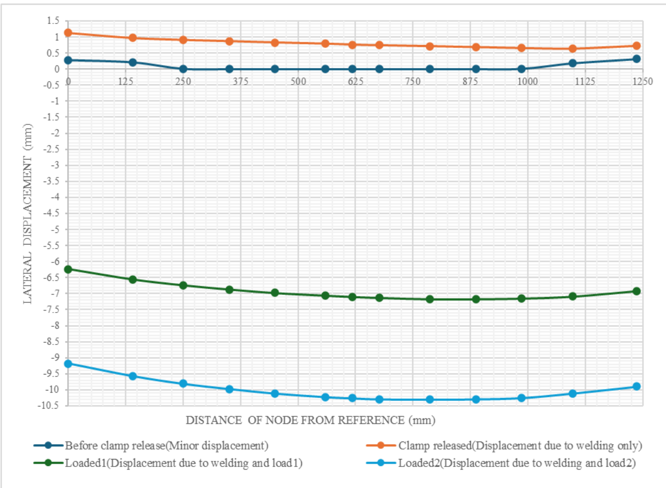

Chart -4: Lateral displacement in horizontal top member (member 2)

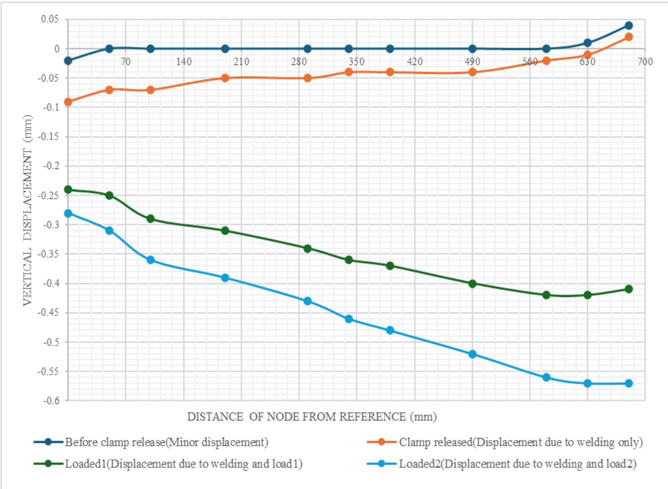

Chart -5: Vertical displacement in diagonal member meeting at the support (member 3)

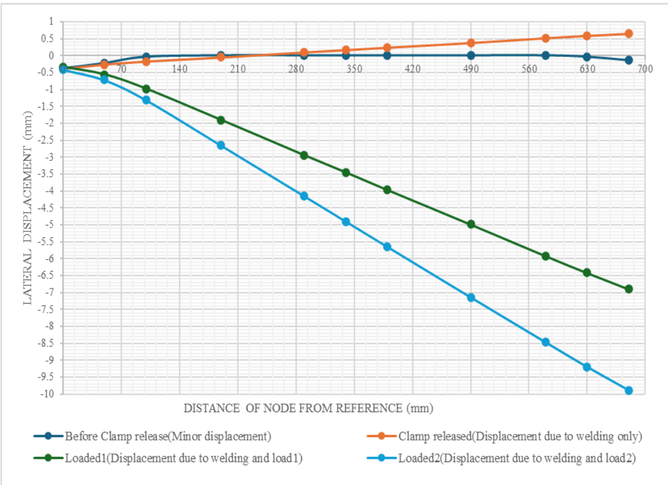

Chart -6: Lateral displacement in diagonal member meeting at the support (member 3)

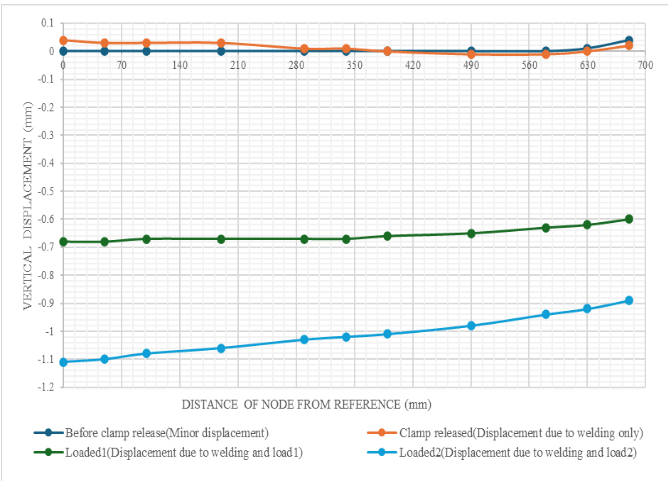

Chart -7: Vertical displacement in diagonal member meeting at the center (member 4)

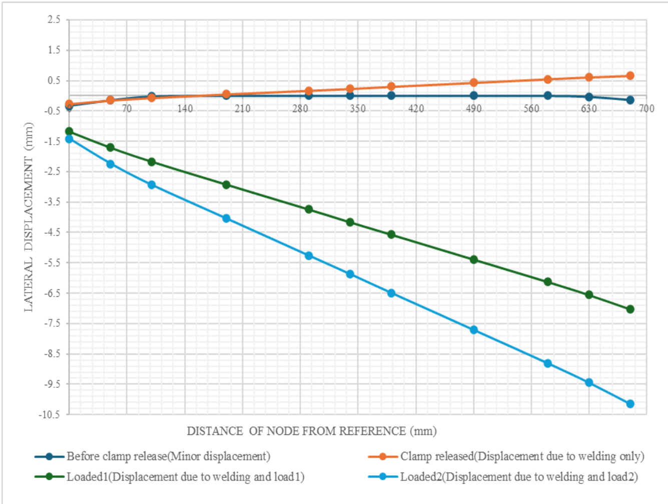

Chart -8: Lateral displacement in diagonal member meeting at the center (member 4)

The charts 1-8 are obtained after performing the simulations to assess the effect of welding on the Warren truss. The results clearly shows that the effect of welding is different for the different members of the truss. Hence the charts for the vertical and lateral displacements in each member of the Warren truss are prepared separately and is analyzed to assess the effect of welding on each member.

Based on the results obtained, the following discussions on the results are presented as follows:

(i) In case of Horizontal base member, Welding increases the vertical displacement at the center but reduces the vertical displacement away from the center. At center for load case 1 maximum of 1.94% increase in vertical displacement and for load case 2 maximum of 1.29% increase in vertical displacement is noticed.

(ii) In case of Horizontal base member, the lateral displacement induced due to given loading is increased due to welding. Due to welding, for load case 1 maximum of 77.27% increase in lateral displacement is noticed. For load case 2 maximum of 42.5% increase in lateral displacement is noticed.

(iii) In case of Horizontal top member, the vertical displacement induced due to given loading is increased due to welding. Due to welding, for load case 1 maximum of 19.79% increase in vertical displacement is noticed. For load case 2 maximum of 14.62% increase in vertical displacement is noticed.

(iv) In case of Horizontal top member, the lateral displacement induced due to given loading is reduced due to welding. Due to welding, for load case 1 maximum of 18.11% decrease in lateral displacement is noticed. For load case 2 maximum of 12.31% decrease in lateral displacement is noticed.

(v) In case of Diagonal member meeting at the support, the vertical displacement induced due to given loading is increased due to welding. Due to welding, for load case 1 maximum of 37.5% increase in vertical displacement is noticed. For load case 2 maximum of 32.14% increase in vertical displacement is noticed.

(vi) In case of Diagonal member meeting at the support, the lateral displacement induced due to given loading is reduced due to welding. Due to welding, for load case 1 maximum of 9.42% decrease in lateral displacement is noticed. For load case 2 maximum of 6.57% decrease in the lateral displacement is noticed.

(vii) In case of Diagonal member meeting at the center, the vertical displacement induced due to given loading is slightly reduced due to welding. Due to welding, for load case 1 maximum of 5.88% decrease in vertical displacement is noticed. For load case 2 maximum of 3.6% decrease in vertical displacement is noticed.

(viii) In case of Diagonal member meeting at the center, the lateral displacement induced due to given loading is reduced due to welding. Due to welding, for load case 1 maximum of 9.39% decrease in lateral displacement is noticed. For load case 2 maximum of 6.5% decrease in lateral displacement is noticed.

6. CONCLUSIONS

The study carried out to assess the effect of welding on the load carrying capacity of the warren truss. The weld input calibration and material calibrations are done. Thermal, metallurgical and mechanical analysis are carried out and based on the results obtained, the following conclusions are drawn:

(i) The effect of welding is noticed to influence the load carrying capacity of truss. The way it influences and the proportion it influences depends on the type of member and the type of truss and weld input parameters.

(ii) The clamp release point of time is found critical, since peak residual stresses and distortions are found due to welding soon after the release of the clamp. Hence the clamp release time must be properly designed to reduce the distortions and residual stresses in the members of truss.

(iii) Outer diagonal members near supports of truss have higher percentage increase in vertical displacement, making them highly sensitive to welding effects, also making them a weak point under welded conditions.

(iv) Base horizontal members and outer diagonal members near the supports are the critical members because of welding.

(v) Load redistribution in Warren trusses appears more efficient, reducing welding-induced stress effects in certain members. And likely due to improved lateral stiffness from welded joints, welding reduces the lateral displacements in diagonal members and top horizontal members.

7. SCOPE FOR FURTHUR STUDY

The study can be extended with the observation of the long-term behavior of the welded trusses subjected to cyclic loading and can assess fatigue durability and fatigue performance. The study about investigation of post weld heat treatment techniques to mitigate residual stresses and to enhance weld quality can be carried out.

8. ACKNOWLEDGEMENT

The authors express gratitude to ESI Software India Pvt. Ltd. for granting access to their software, which was immensely beneficial in the successful completion of the work.

9. REFERENCES

[1] Manik, Halder P K, Paul N and Shamimur Rahman, “Effect of welding on the properties of mild steel & cast-iron specimen”, ‘International Conference on mechanical, industrial and energy engineering’, 2012.

[2] Van Nhat Nguyen, Quoc-Manh Nguyen and Shyh-Chour Huang, “Study Computational Simulation and Experimental of Tee-Joint by Visual-Weld Software and Tungsten Inert Gas Welding Process”, ‘IEEE International Conference on Advanced Materials for Science and Engineering’- IEEE-ICAMSE 2016.

[3] Tadano Satoshi, Mizuuchi Rieko, Sugiura Kouji and Nakatani Yujiro, “Experimental and numerical study of welding deformation in truss structure of steel angles”, 2019/page 52-58.

[4] Okonkwo V. O., Onodagu P. D. and Udemba J. N, “An Investigation on the Effects of Rigid Joints on the Weight and Load Carrying Capacity of Steel Trusses”, ‘IOSR Journal of Engineering (IOSRJEN)’, Vol. 11, Issue 3, March 2021/page 33-39.

[5] Mohamed M. Ali and Moatasem M. Kh, “Effects of Welding Parameters on Characterization and Mechanical Properties of Steel 37 Weldments”, ‘Journal of Engineering Sciences’, Vol. 48, No. 2, March 2020, PP. 212–221.

[6] Dengyiding Jin, ChaoHou and Luming Shen, “Effect of welding residual stress on the performance of CFST tubular joints”, ‘Journal of Constructional Steel Research’, Elsevier-2021.

10. BIOGRAPHIES

Mr. Murali S, M.Tech student (Structural Engineering), UVCE Bangalore. Completed B.E in Civil Engineering from BIT, Bangalore.

Dr. Chethan K, Associate Professor, Department of Civil Engineering, UVCE, Bangalore. Has completed M.Tech (Industrial Structures-NITK) and PhD (NITK).

Dr. Achutha Herur Gopalaiah, Sr. Manager PO/PMO, ESI Software India Pvt. Ltd. Bengaluru. Has completed M.E (Structural Mechanics, MSRIT) and PhD (UVCE).