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Simulation Study of Static and Fatigue Behaviour on a Bogie Frame using Mesh-Free and Conventional FEM

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ABSTRACT

This research is devoted to study the simulation of fatigue behaviour for bogie frames using the finite element method (FEM) and mesh-free. The bogie frame is the main structure that supports repeated loads from external forces on the railway car. This study used Altair SimSolid for static and fatigue analyses with a mesh-free method while Altair HyperLife simulated the fatigue analysis using meshed finite element methods (FEM) supported by Altair Hyperworks for static analysis results. This research adopted this method because traditional models for calculating fatigue life have limitations that can lead to inaccuracies and unreliability. Cyclic loading is applied to the frame for simulating real-life conditions and determining its fatigue life. The frame is made of low-carbon steel and subjected to two vertical force loads of 196.2 kN, each supported by four fixed points at the bogie frame's ends. The Von Mises stress values obtained for the frame are 20.71 MPa for the FEM and 19.138 MPa for the mesh-free method. According to the fatigue life analysis, Altair HyperLife and Altair SimSolid yield fatigue life value for channel scale one, and channel scale 15 yields 100E cycles. A red contour shows the presence of damage.

Keywords: Fatigue; Mesh FEM; Mesh-free; Fatigue life; Fatigue damage.

Abbreviations

FEM	Finite Element Method
FEA	Finite Element Analysis
RBE3	Rigid Body Element (type 3 constraint element)
SPC	Structural Point Constraint
SN Curve	Stress–Number of cycles fatigue curve

1.0 INTRODUCTION

As an engineer, structure design and material behaviour awareness are crucial in predicting the service life of any structure [1-3]. Fatigue tests help determine the expected service life of a component or structure subjected to repeated cyclic loading [4-6]. By subjecting the material or structure to controlled cyclic loading, the test provides valuable data on how it will perform over time in service conditions. This information is essential for ensuring the reliability and safety of various mechanical structures. Fatigue tests allow researchers and engineers to study the fatigue behaviour of materials and structures. Structural fatigue analysis provides insights into the accumulation of damage, crack initiation and propagation, and failure mechanisms under cyclic loading [7-8]. This knowledge helps in developing accurate fatigue models and designing components with improved fatigue resistance.

Due to the competitive nature of engineering design nowadays, numerical computational methods are used to reduce the lead time and cost of any mechanical structure development before the fabrication process occurs [1,9]. Numerical simulation, also known as computer simulation or computational modelling, offers advantages such as design optimization [10-12]. Simulation facilitates design optimization by providing insights into system behaviour and performance under different conditions. Engineers can assess and compare multiple design alternatives, materials and parameters to identify the optimal solution.

This helps improve efficiency, reliability, and safety while reducing costs and potential risks. Another advantage is early structure performance evaluation. Numerical simulation allows engineers to predict the performance and behaviour of systems or structures before their physical implementation [13]. By accurately modelling the physics and dynamics involved, simulation can provide valuable information about stress distribution, fluid flow, heat transfer, and other critical factors. This helps in evaluating system performance, identifying potential issues, and making informed decisions. Computer numerical simulation can also help to analyse complex phenomena that are difficult to observe or measure directly.

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The finite element method (FEM) is widely used for simulating structural behaviour and fatigue response in engineering applications [14-21]. In fatigue simulation, FEM is commonly used to analyse stress distribution and fatigue behaviour in structural components, where previous studies have shown that critical stress concentrations typically occur near support and joint regions, significantly influencing fatigue life prediction [22,23]. The meshed FEM approach provides a systematic and efficient way to model fatigue behaviour and capture stress concentration effects. By refining the mesh in critical regions or around crack tips, FEM can accurately capture local stress gradients and predict fatigue life. However, these studies primarily focus on conventional FEM approaches, and limited work has investigated the comparative performance of mesh-free methods for such structural applications.

Mesh-free methods have been developed as an alternative numerical approach to improve computational efficiency, particularly for complex geometries [24]. These methods are particularly useful for complex geometries or situations where mesh generation is challenging. In fatigue simulation, mesh-free methods can capture material behaviour more accurately in regions with large deformations, cracks, or local stress concentrations [25]. Mesh-free methods are also beneficial for simulating crack propagation and interactions with complex geometries. This approach provides a flexible framework for modelling fatigue behaviour and can handle large deformations and topological changes [26,27]. Although mesh-free methods offer advantages in handling complex geometries, existing studies indicate that their application in structural fatigue analysis remains limited, particularly in comparison with conventional FEM for large-scale structures such as bogie frames.

This study aims to compare the capability of conventional FEM and mesh-free methods in predicting stress distribution and fatigue behaviour of a bogie frame under cyclic loading conditions. By analysing the fatigue behaviour under cyclic loading, researchers and engineers can determine the most effective approach for dealing with the fatigue problem. By utilizing computational numerical methods, this study has the potential to significantly improve the understanding of fatigue life and failure mechanisms in materials and structures, thus avoiding catastrophic failure.

2.0 METHODOLOGY

2.1 Geometry Modelling and Meshing for Bogie Frame

The bogie frame consists of two side frames and two central beams, designed to support the lifting and transportation of loads. Figure 1 shows the model utilized in this study is commonly referred to as the flat bogie frame. Table 1 shows parameters and surface area maintained throughout the design process.

The geometry was discretised into four-node linear tetrahedral elements with a global element size of 4 mm. The material attributes listed in Table 2 have been sourced from the Altair material database. These properties provide valuable information regarding the mechanical and thermal properties of low carbon steel.

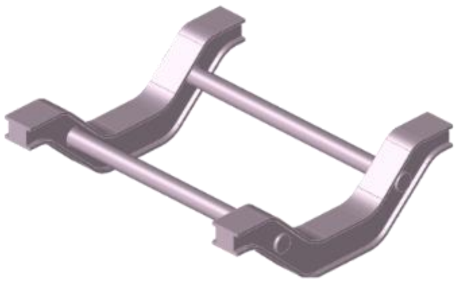


Figure 1. Bogie frame model

Table 1. Dimension of the Bogie frame.

Dimension	Parameter
Width	2.47 m
Length	2.29 m
Height	0.71 m
Weight	2806.24 kg

Table 1. Material properties of low carbon steel from Altair Hyperworks database.

Properties	Value
Elasticity Modulus	$2100\ GPa$
Poisson Ratio's	0.3
Density	$7.85 \times 103\ kg/m^3$
Ultimate Tensile Stress	$345\ MPa$
Tensile Yield Stress	$207\ MPa$
Compressive Yield Stress	$207\ MPa$
Thermal expansion coefficient	$1.2 \times 10^{-5}\ K^{-1}$

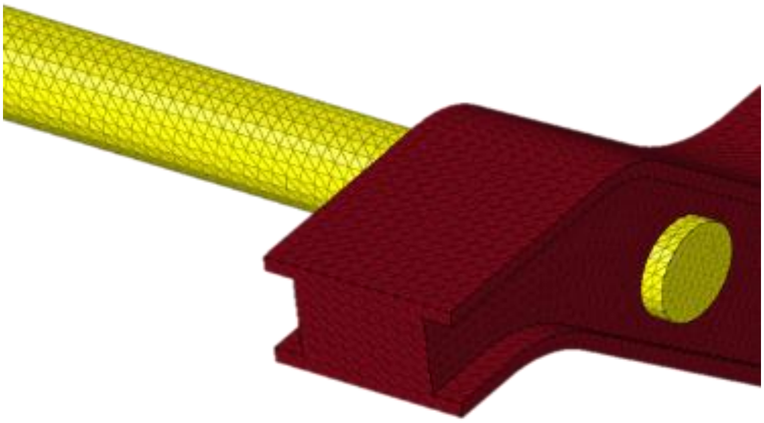
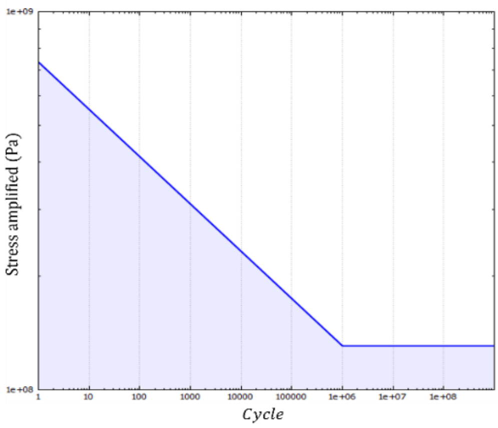
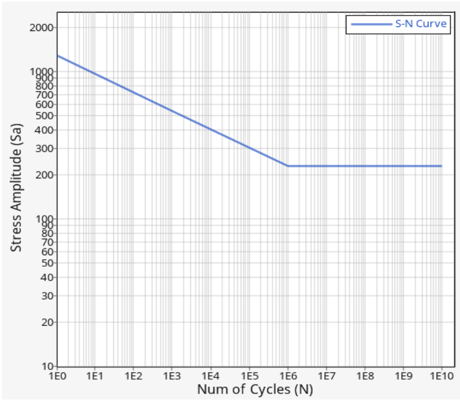


Figure 2. Meshing on the Bogie frame.



(a)



(b)

Figure 3. S-N curve for (a) steel obtained from Altair SimSolid material database and; (b) low carbon steel obtained from Altair HyperLife material database.

Before exerting force on the component in HyperWorks, the model must be discretised as part of the finite element analysis (FEA) procedure. The meshing process shown in Figure 2 involves dividing the geometry into four-node linear tetrahedral elements. A global element size of 4 mm was applied to the bogie frame to balance computational efficiency and model size due to the large geometry of the structure. Relatively finer discretisation occurs near regions such as the fixed supports where stress concentration is expected. This discretisation enables reliable prediction of structural behaviour under the applied loading conditions.

On the other hand, SimSolid can apply force and support directly without requiring meshing or the use of RBE3 elements because it utilizes the external approximation method. This procedure enables SimSolid to calculate reaction forces precisely without mesh or finite element analysis.

Based on Altair SimSolid material database shown in Figure 3 (a), the highest stress that steel can sustain is around 700 MPa, while stress less than 130 MPa is expected to achieve infinite life or unlock endurance life. In Figure 3 (b), the S-N curve shows the highest stress that low-carbon steel can withstand is 1.3 GPa, and the endurance life is below 0.23 GPa.

2.2 Mechanical Constraint Set-Up at structure

Boundary conditions are defined by applying four fixed supports at the ends of the bogie frame and two vertical loads at the central beam. The boundary condition on the bogie seen in Figure 4 is critical for ensuring that the simulation appropriately replicates real-world conditions. Four fix supports (red circle) are applied at the end of the bogie frame, with two forces (green box) applied to the center frame.

In Altair Hyperworks, the procedure for applying the constraint to the bogie is intricate because of the finite element. In order to generate distribution load on the bogie frame using the finite element method (FEM), the initial step involves creating a Rigid Body Element (RBE3) and selecting the appropriate bogie points to apply Structural Point Constraints (SPC). RBE3 connects the selected bogie's node to a master node, which implements constraints to all connected nodes simultaneously. RBE3 is a powerful FEM analysis tool that connects several nodes to a master node. Figure 5 shows the applied loading conditions in (a) Altair HyperWorks and (b) Altair SimSolid, where a load of 196.2 kN was applied at each loading point, resulting in a total load of 392.4 kN (approximately 40 tons). The conventional FEM model applies constraints using RBE3 elements and structural point constraints, whereas the mesh-free model applies loads and supports directly without meshing.

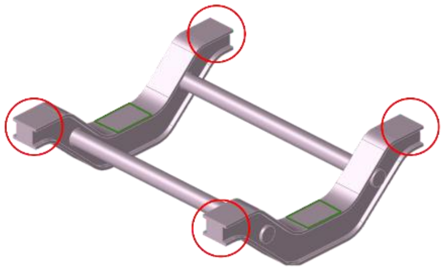
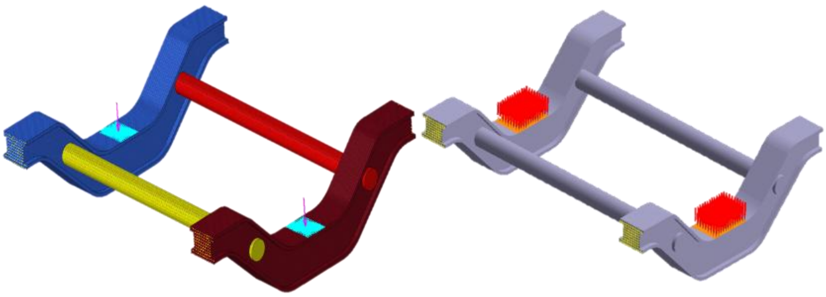


Figure 4. Boundary condition on the bogie frame.



(a) (b)

Figure 5. The loadings acting on the boogie using (a) Altair Hyperworks and; (b) Altair SimSolid.

2.3 Defining Load Cycle

Cyclic loading was applied to evaluate the fatigue behaviour of the bogie frame. The analysis was conducted using a loading frequency of 1 Hz for a total of 500,000 cycles, as shown in Figure 6. The selected frequency represents a simplified cyclic loading condition and does not directly correspond to a specific train speed or wheel rotation frequency but provides a controlled basis for comparative analysis between the two methods. The channel scale factor was used to vary the loading amplitude, where a scale of 1 represents the baseline condition and a scale of 15 represents an amplified loading scenario. The same loading configuration was applied consistently in both Altair HyperWorks and Altair SimSolid to ensure a fair comparison.

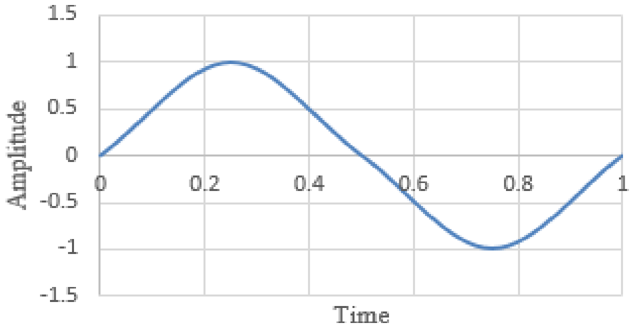


Figure 4. Illustration of harmonic loading at 1 Hz.

3.0 RESULTS AND DISCUSSION

Table 3 summarises the von Mises stress and displacement obtained from both methods under identical loading conditions. The results show a small difference in von Mises stress between the two methods, while the Y-displacement values are nearly identical. The difference in von Mises stress is attributed to differences in numerical formulation and discretisation approach between conventional FEM and the mesh-free method. The bogie frame is modelled as a single continuous component in both approaches, ensuring that the observed differences are due to the analysis method rather than geometric representation.

The contour plot shows that the highest stress concentration occurs near the fixed support region, which is consistent with the applied boundary conditions. Similar stress distribution patterns are observed for both methods, indicating comparable structural response. Table 4 shows that no fatigue damage is observed at channel scale 1, indicating that the stress level remains below the material endurance limit. As a result, the predicted fatigue life approaches the upper limit defined in the software.

Table 5 shows that the channel scale increased to a value of 15, resulting in a significant increase in fatigue damage. This increase is associated with the higher stress amplitude, where the stress level reaches approximately 300 MPa under the amplified loading condition. The results indicate that the initial signs of damage occurred at the ends of the bogie frame, which correspond to regions subjected to constraints. The presence of high stress concentration in these areas leads to the formation of localized damage, as observed from the contour results. Consequently, the increase in loading amplitude accelerates fatigue damage accumulation and significantly reduces the fatigue life in these critical regions. The lowest fatigue life is consistently observed near the fixed support areas, indicating that these regions are the most susceptible to failure due to combined effects of constraint and stress concentration.

Table 3. Result of static analysis on bogie frame.

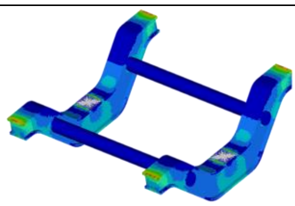
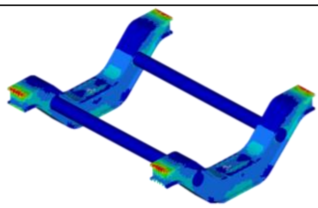
Software	Altair Hyperworks	Altair SimSolid
		
Von Mises Stress	20.71 MPa	19.138 MPa
Y-Displacement	-0.0637 mm	-0.0629 mm

Table 2. Result of fatigue analysis on bogie frame for channel scale of 1.

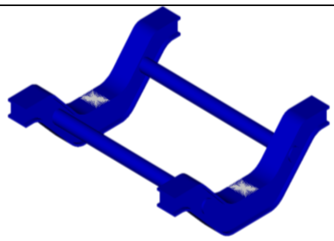
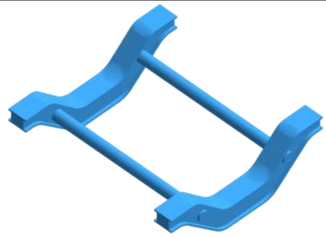
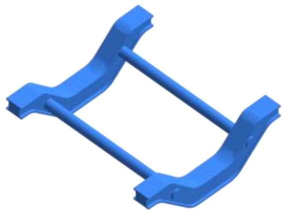
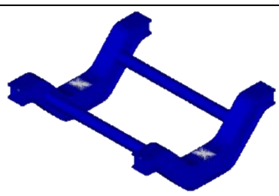
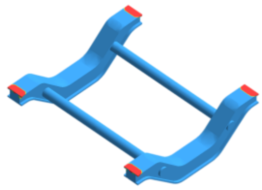
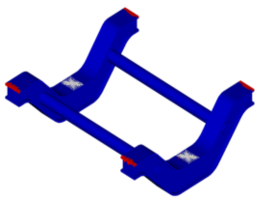
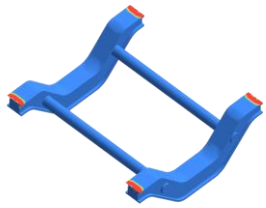
Software	Altair HyperLife	Altair SimSolid
Damage contour		
Fatigue Damage	0	0
Life Contour		
Fatigue Life	1E+20 (min), 1E+20 (max)	1E+20 (min), 1E+20 (max)

Table 3. Result of fatigue analysis on bogie frame for channel scale of 15.

Software	Altair HyperLife	Altair SimSolid
Damage contour		
Fatigue Damage	66.96	164.69
Life Contour		
Fatigue Life	0.0149 (min), 1E+20 (max)	0.00658 (min), 1E+20 (max)

At channel scale 15, the fatigue damage values increased to 66.96 for Altair HyperLife and 164.69 for Altair SimSolid. In the stress–life fatigue formulation adopted by the software, a damage value of 1 represents the threshold for failure initiation. The obtained damage values significantly exceeded this limit, indicating that fatigue failure is predicted to occur before completion of the defined 500,000 loading cycles. Both methods therefore predict premature fatigue failure under the amplified loading condition.

The minimum fatigue life values of 0.0149 (HyperLife) and 0.00658 (SimSolid) represented the fraction of the applied loading block at which failure is expected. Converting these ratios into actual cycles gives approximately 7,450 cycles and 3,290 cycles, respectively. These results indicate that under channel scale 15, the bogie frame cannot endure the cyclic loading and failure is predicted to initiate at the fixed support regions where stress concentration is highest.

A clear distinction was observed between the two loading scales. For channel scale 1, zero fatigue damage was recorded and the predicted fatigue life approached the upper computational limit, indicating that the stress level remains below the endurance limit. In contrast, increasing the channel scale to 15 raised the stress amplitude to approximately 300 MPa, resulting in rapid damage accumulation and predicted failure within a few thousand cycles. This demonstrates that the bogie frame remains structurally safe under baseline loading but becomes fatigue-critical when subjected to amplified cyclic loading.

4.0 CONCLUSION

Both techniques have their advantages and disadvantages. The external approximate by finite element in Altair SimSolid is known for its efficiency and ability to handle complex geometries with the boundary element method. On the other hand, the finite element method simulated by Altair Hyperworks and Altair HyperLife is more versatile and can accurately capture complex physical behaviours. Depending on the specific analysis requirements, engineers can choose the appropriate software for their simulation needs. According to the results obtained, the following conclusions are presented:

i. The static analysis simulation conducted using Altair Hyperworks and Altair SimSolid yielded successful outcomes in terms of Von Mises stress and Y displacement. The Von Mises stress values obtained from Altair Hyperworks and Altair SimSolid are 20.71 MPa and 19.138 MPa, respectively and the Y-displacement values for the two simulations are 0.0637 mm and 0.0629 mm, respectively.
ii. Excessive stress on the fixed support area might lead to catastrophic failure of the bogie frame and compromise the safety of the train.
iii. The computational time of using Altair SimSolid is almost instant compared to traditional FEM by using Altair Hyperworks.

Based on the simulation, the bogie frame can endure the load that has been exerted with channel scale 1, and the fatigue life of the frame that has been estimated is 1E+20, while by channel scale 15, the initiation of a propagation on the bogie frame is beginning to be visible.

Further research can be performed as a recommendation:

i. To investigate complex structures to the computational time and accuracy software by using Altair Hyperworks and Altair SimSolid.
ii. To investigate different loading frequencies and cycle numbers to optimize structure design and remodel the structure.
iii. To study the mean stress correction, surface finished, and surface treatment and compare between software.

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AUTHORS CONTRIBUTION

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

DECLARATION OF COMPETING OF INTEREST

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agreed with its submission and declared no conflict of interest on the manuscript.

REFERENCES

[1] M. Quaresimin, L. Susmel, and R. Talreja, "Fatigue behaviour and life assessment of composite laminates under multiaxial loadings," *International Journal of Fatigue*, vol. 32, no. 1, pp. 2–16, 2010.

[2] C. Feng, M. Su, L. Xu, L. Zhao, and Y. Han, "A unified prediction approach of fatigue life suitable for diversified engineering materials," *Engineering Fracture Mechanics*, vol. 290, p. 109478, 2023.

[3] S. Gbagba, L. Maccioni, and F. Concli, "Advances in machine learning techniques used in fatigue life prediction of welded structures," *Applied Sciences*, vol. 14, no. 1, p. 398, 2023.

[4] G. Antaki and R. Gilada, "Design basis loads and qualification," in *Nuclear Power Plant Safety and Mechanical Integrity*, Elsevier Ltd., pp. 27–102, 2015.

[5] H. Jahed and A.A.A. Roostaei, *Cyclic Plasticity of Metals: Modeling Fundamentals and Applications*, Elsevier series on plasticity of materials, Elsevier Science, 2021.

[6] R. Jimit, K. Zakaria, O. Bapokutty, M. Ali, and A, Rivai, "Fatigue life behaviour of fiberglass-reinforced composites subjected to underloading," *Journal of Advanced Manufacturing Technology*, vol.14, no. 2, 2020.

[7] H. Mayer, *Recent Developments in Ultrasonic Fatigue*, Blackwell Publishing Ltd., 2016.
[8] Z. Barsoum, *Guidelines for Fatigue and Static Analysis of Welded and Un-Welded Steel Structures*, KTH Royal Institute of Technology, Stockholm, Sweden, 2020.
[9] M. Jamli, "Finite element analysis of springback process in sheet metal forming," *Journal of Advanced Manufacturing Technology*, vol. 11, no. 1, pp. 75-84, 2017.
[10] S. Liu *et al.*, "A review of welding simulation methods for large components," *Progress in Natural Science: Materials International*, vol. 33, no. 5, pp. 551–568, 2023.
[11] A. Divyeshkumar, D. Ashish and M. Amrat, "Numerical simulation of arc welding," *International Journal for Multidisciplinary Research*, vol. 6, no. 2, 2024.
[12] P. Maćkowiak and D. Płaczek, "Numerical simulation of the welding process for the prediction of temperature distribution on Al/steel explosion welded joint," *Journal of Physics: Conference Series*, vol. 2714, no. 1, p. 012020, 2024.
[13] A. Aflaki, M. Esfandiari, and S. Mohammadi, "A review of numerical simulation as a precedence method for prediction and evaluation of building ventilation performance," *Multidisciplinary Digital Publishing Institute*, 2021
[14] B. Szabo and I. Babuska, *Finite Element Analysis*. Wiley, 2021.
[15] R. Ramanathan, L. Abdullah, M. Md Fauadi, M. Syed Mohamed, M. Aras, and A. Nur Chairat, "Mechanical stress-strain analysis of a portable oil spill skimmer frame for response and recovery activities," *Journal of Advanced Manufacturing Technology*, vol. 17, no. 1, 2023.
[16] O.C. Zienkiewicz, R.L. Taylor and J.Z. Zhu, *The Finite Element Method: Its Basis and Fundamentals*, 6th Edition, Elsevier Butterworth-Heinemann, 2005.
[17] L. B. Wahlbin, *Local Behaviour in Finite Element Methods*, Elsevier Ltd., North Holland, 1991.
[18] Y. Jia *et al.*, "A new nodal-integration-based finite element method for the numerical simulation of welding processes," *Metals (Basel)*, vol. 10, no. 10, p. 1386, 2020.
[19] A.A. Khan, F. Shahid, and I. Qamar, "Development of finite element solver for welding analysis," *Smart Construction Research*, vol. 2, no. 2, 2018.
[20] M. Freire-Torres, M. Colera, and J. Carpio, "Numerical solution of thermal phenomena in welding problems," *Mathematics*, vol. 11, no. 13, p. 3009, 2023.
[21] S. Das, *Discrete Finite Elements*, Spriger, 2023, pp. 13–70.
[22] M. Kumar, R.K. Gupta, V. Kumar and P. Bhatt, "Fracture mechanics and fatigue analysis in structural engineering," *Tuijin Jishu/Journal of Propulsion Technology*, vol. 44, no. 3, pp. 3056–3062, 2023.
[23] A.M. Alshoaibi and Y.A. Fageehi, "Advances in finite element modeling of fatigue crack propagation," *Applied Sciences*, vol. 14, no. 20, p. 9297, 2024.
[24] S. Garg and M. Pant, "Meshfree methods: A comprehensive review of applications," *International Journal of Computational Methods*, vol. 15, no. 4, 2018.
[25] W. Ma, G. Liu, and W. Wang, "A coupled extended meshfree–smoothed meshfree method for crack growth simulation," *Theoretical and Applied Fracture Mechanics*, vol. 107, 2020.
[26] M. Zhang, A.R. Zainal Abidin and C.S. Tan, "State-of-the-art review on meshless methods in the application of crack problems," *Theoretical and Applied Fracture Mechanics*, vol. 131, p. 104348, 2024.
[27] S. Chen, "Mesh-free methods with special focus on EFGM," 2023, pp. 593–654, 2023.
[28] Y. Yamazaki *et al.*, "Development of fatigue prediction system for bogie frame using a dynamic analysis model based on high-speed and high-precision stress estimation method," *Electrical Engineering in Japan*, vol. 217, no. 3, 2024.