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Comparing Bolt Implementation Methods in Vibration Testing for Accurate Dynamic Behavior Analysis

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Abstract: Vibration testing is crucial for understanding structural dynamics, yet conventional modeling of bolt connections often leads to significant inaccuracies. This study systematically compares six bolt connection methods—bonded, adaptive bonded, joint, beam, screw, and fixed bolt—using a finite element analysis of a headlamp vibration test jig. The six bolt connection methods were selected based on approaches adopted in previous studies. The experimental results identified the joint connection method as the most accurate, minimizing deviations in natural frequency to 7.6 Hz compared to experimental tests at 493.2 Hz, while bonded methods overestimated the frequency at 544.1 Hz due to excessive stiffness assumptions. Efficiency analyses highlighted bonded methods as the most computationally streamlined, offering preprocessing times as short as 30 s and shorter overall analysis times. These findings emphasize the importance of selecting appropriate bolt connection methods in the early design phase to ensure accurate natural frequency predictions and mode shape representations. Although this study does not consider bolt preload forces, the work shows the possibility of offering practical guidelines for improving the reliability and efficiency of vibration test jig designs by bridging the gap between analysis and experimental results.

Keywords: bolt implementation; dynamic behavior analysis; vibration testing; finite element analysis

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1. Introduction

Vibration testing provides critical data for assessing the safety and durability of a structural design by analyzing the natural frequencies and mode shapes of the structure [1,2]. This analysis is crucial for understanding the dynamic behavior of structures and assessing design suitability and durability [3–5]. Resonance at specific frequencies, in particular, can increase component fatigue and reduce durability, making design review and vibration testing an essential preventative step [6–8]. These vibration tests are performed by fixing the structure under test. A jig is required to obtain accurate test results with natural frequencies and mode shapes superior to those of the test object [9]. This is because the influence of the jig's properties on the test results is minimized, enabling an accurate evaluation of the actual durability performance of the structure [10].

Vibration test jigs are typically assembled using ribs and plates fastened with bolts. The bolt connection method significantly affects properties such as rigidity and natural frequency [11–13]. In the early design stages, bolt connections are often simplified and modeled as bonded (perfect bonding) to improve analysis efficiency. Although this approach reduces analysis time, it fails to fully capture the actual contact behavior of bolt

connections, leading to discrepancies between the analysis and test results [14–16]. This hinders the derivation of accurate test results and increases the likelihood that the jig design properties will not meet expectations under real-world conditions.

The bolt connection method significantly affects the natural frequencies and mode shapes of a vibration test jig. Therefore, differences may arise between the analysis and experimental results depending on the contact conditions and connection method chosen [11]. Numerous studies have analyzed the effects of bolt connection methods on the natural frequencies and mode shapes of structures through experiments and numerical analysis, emphasizing their critical role in ensuring design accuracy and appropriateness [17,18]. For instance, a study showed that failing to reflect the actual contact conditions of the bolts during vibration testing can reduce the consistency between the analysis and experimental results, highlighting the importance of proper bolt implementation methods to improve design accuracy [19]. Additionally, a study that experimentally demonstrated the impact of bolt connection methods on natural frequencies and mode shapes suggested that selecting the correct connection method during the initial design stage is essential [20].

To address the discrepancy between analysis and test results, various bolt implementation methods have been proposed [21]. For example, connecting a line body under rigid conditions can improve analysis efficiency by providing shorter analysis times in vehicle engine vibration testing [22]. Furthermore, the simplified connection approach has been effectively applied in the vibration analysis of diesel engine cylinders, streamlining bolt implementation while maintaining adequate accuracy [23]. However, research on bolt implementation methods in vibration testing remains fragmented, and a systematic comparison and evaluation of the performance and limitations of each method are lacking.

This study analyzes the natural frequencies, mode shapes, and efficiency of various bolt implementation methods using a vibration test jig to determine the most suitable method for design and analysis. To achieve this, a headlamp jig and M6 standard tapped bolts currently in use were selected as the research materials. The bolts were modeled using six different implementation methods, and their natural frequencies, mode shapes, analysis times, and preprocessing efficiency were compared. Additionally, the natural frequencies obtained from vibration tests were compared with those of the analysis models to evaluate the effectiveness of each method. Through this analysis, this study seeks to provide practical guidelines for design and analysis stages, contributing to improved accuracy and efficiency in structural design.

2. Materials and Methods

2.1. Specifications

In this study, M6 standard tapped bolts were selected as the research model. These bolts are used in actual vibration tests to connect the ribs and feature a design that forms internal threads directly on the counterpart without requiring nuts, particularly in situations where through-holes cannot be drilled. Figure 1 and Table 1 present the dimensions and specifications of the M6 bolts used in this study.

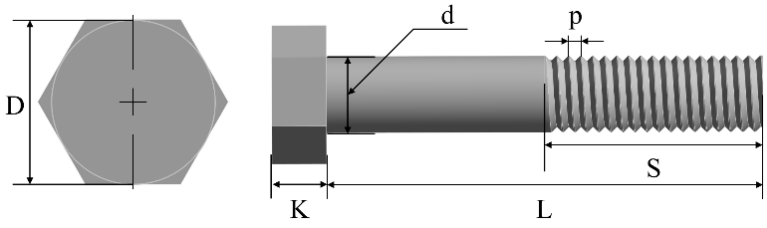


Figure 1. M6 bolt dimensions.

Table 1. M6 bolt dimensions.

	Length [L]	Diameter [d]	Head Diameter [D]	Head Thickness [K]	Pitch [p]	Threaded Length [S]
Dimension (mm)	40	6	10	4	1	20

Figure 2 shows the headlamp vibration test jig used for analysis and testing. Headlamps are continuously exposed to vibration and shocks during operation, making vibration testing essential. Furthermore, the headlamp vibration test jig, which requires numerous bolt fastenings, is well-suited for comparing behaviors based on bolt fastening methods. The jig weighed 67.8 kg and comprised 14 ribs, 2 lamp-fastening sections, and 1 lower plate. The ribs were 20 mm thick, while the lower plate was 25 mm thick, with dimensions of 892.4 mm along the *x*-axis and 652.7 mm along the *y*-axis. The jig's overall height, measured from the top of the lower plate, was 628.8 mm. A total of 291 bolt holes were created on the jig at 30 mm intervals, with additional holes at 100 mm intervals on the lower plate for attachment to the vibration testing machine (Figure 2).

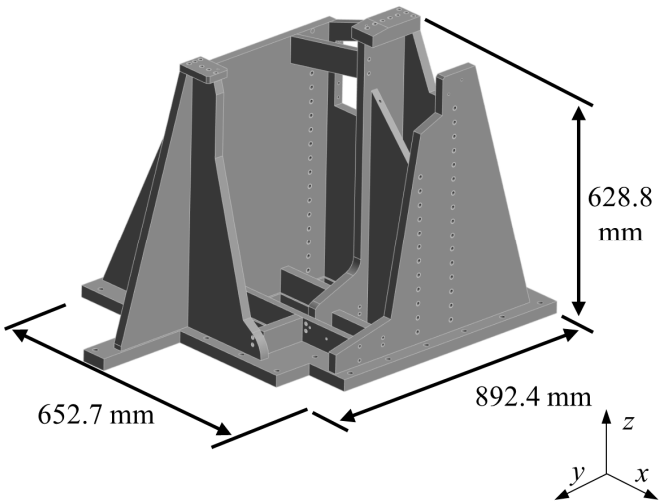


Figure 2. Structure and fastening positions of the vibration test jig for a headlamp.

2.2. Finite Element Analysis

In this study, six methods were used to simulate bolt connections: bonded, adaptive bonded, joint, beam, screw, and fixed bolt. The six selected methods in this study represent the functions for a bolt simulation available in ANSYS and Inspire (i.e., widely used commercial software). The adaptive bonded, joint, and beam methods were provided in ANSYS, while the screw and fixed bolt methods were provided in Inspire. Particularly, the adaptive bonded and beam methods were used in previous studies, such as those that analyzed diesel engine vibrations [23], and the joint method was also frequently applied in engine vibration testing research [22]. On the other hand, the screw and fixed bolt methods were included in this study for comparative purposes although they were not widely studied. Figure 3 shows the fastening appearance of the bolts used. In addition, Figure 4 shows the application sequence of the proposed method in a flow chart.

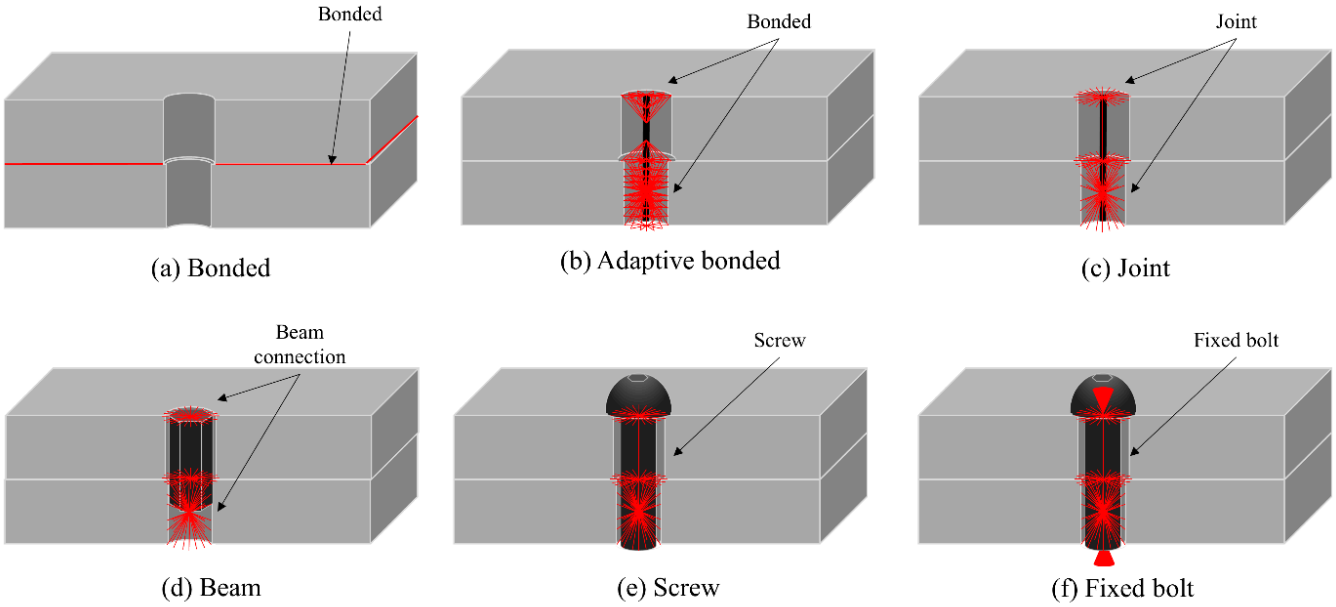


Figure 3. Implementation methods for bolt connections.

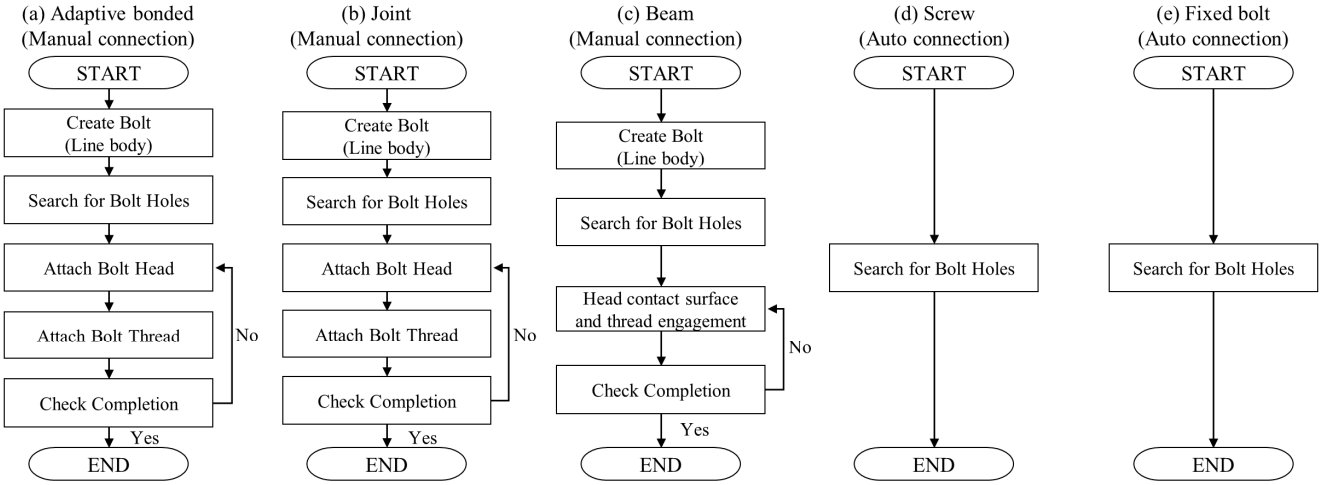


Figure 4. Implementation procedures for bolt connections.

The bonded connection method (Figure 3a) establishes a fully bonded state by applying bonded conditions to the contact area without modeling the bolt. Contact conditions are applied to prevent deformation or slippage on all contact surfaces, ensuring a solid bond between structures. This method assumes that the entire joint area acts as a rigid body, regardless of the contact area, thus representing high bonding strength. This connection method was implemented using the "Contacts" tool in ANSYS Connections.

The adaptive bonded connection method (Figure 3b) models bolts as line bodies, assigning contact areas and bonded conditions to connect them. To implement this, bolts are created by connecting two line bodies. These line bodies are divided into threaded and non-threaded sections for representation. At the non-threaded sections, contact conditions are applied to the upper and lower edges of the holes to simulate a weaker bonding strength. Additionally, contact conditions are applied between the line bodies and surfaces with internal threads to represent the threaded contact. This connection method was implemented using the "Contacts" tool in ANSYS Connections.

The joint connection method (Figure 3c) models bolts as line bodies and rigidly connects them with the contact areas. Bolts were created as line bodies in the same way as in the adaptive bonded method. For contact representation, the non-threaded

sections of the line body were assigned contact conditions at the upper and lower edges. Additionally, the threaded sections were assigned contact conditions between the line body and the internal thread surfaces. This method was implemented using the "Joint" tool in ANSYS Connections.

The beam connection method (Figure 3d) implements bolts as virtual beam elements and rigidly connects the contact areas. A notable feature of this method is that it does not require prior creation of bolt bodies. Unlike the adaptive bonded method, where bolt contacts are specified separately, the creation of beams directly serves as the bolt representation. Therefore, contact conditions are directly applied to the edge of the surface where the bolt head is fastened and the area on the lower plate where the internal threads are located. This method was implemented using the "Beam" tool in ANSYS Connections.

The screw connection method (Figure 3e) models bolts as line bodies and connects the contact areas using Rigid Body Element 2 (RBE2) constraints. RBE2 ensures that all connected nodes behave as a rigid body, maintaining identical displacements and rotations across the nodes. In the screw connection method, bolts could be created simply without requiring additional contact conditions or the need to locate bolt positions. This method simplifies fastening, enabling efficient modeling and analysis. This connection method was implemented using the "Fastener" tool in the Inspire analysis program.

The fixed bolt connection method (Figure 3f) also models bolts as line bodies and connects the contact areas using RBE2 constraints. Unlike the screw connection method, the nodes at the top and bottom of the CBAR are designated as fixed points, ensuring that both ends of the bolt remain completely fixed. Similar to the screw connection method, the fixed bolt method allows bolts to be created simply without assigning additional contact conditions or locating bolt positions. The fixed bolt method provides a fastening method that simulates connections where rigidity is relatively important. This connection method was implemented using the "Fastener" tool in the Inspire analysis program.

For the representation of line bodies, BEAM188 elements were used in ANSYS analysis, while CBAR elements were used in Inspire. BEAM188 elements have the characteristic of allowing thickness information to be input for one-dimensional structures. Additionally, these elements have six degrees of freedom and can account for axial forces, shear forces, bending, and torsion moments. CBAR elements have the same degrees of freedom and can similarly represent the physical properties of bolts.

In general, computational analysis results tend to indicate higher natural frequencies compared to experimental values, as they cannot perfectly account for all conditions. To address this, contact friction between contact areas, excluding bolt joints, was not considered in the contact conditions. This assumption was based on the relatively small contact area between the ribs. In addition, the bolts, positioned at 30 mm intervals, were considered sufficient to provide the necessary structural strength for the connection [24]. Moreover, the preload of the bolts was excluded, as it could excessively influence the computational analysis results by further increasing the structural strength.

Figure 5 shows the finite element model of the entire jig. The FE model of the jig was constructed using SOLID185 in ANSYS, 8-node solid elements. This element uses the simplified enhanced strain formulation. Enhanced strain formulation modifies gradient tensor and strains in lower-order elements to prevent shear and volumetric locking [25]. The model consisted of 1,094,136 nodes and 627,725 elements, with an average aspect ratio of 2.31 and an average Jacobian ratio of 0.97, indicating sufficient mesh quality [26]. The detailed calculations are provided in Appendices A and B. The bolt material properties were assigned based on AISI 304 stainless steel (density: 8×10^{-6} kg/mm^3, Young's modulus: 195.0 GPa, Poisson's ratio: 0.29, and yield strength: 215 MPa). The jig material properties were assigned based on Aluminum Die Casting (ALDC) (density: 2.75×10^{-6} kg/mm^3,

Young's modulus: 69.6 GPa, Poisson's ratio: 0.33, and yield strength: 165 MPa). The analysis was conducted using the ANSYS 24 R1 and Inspire 2023 programs. A personal computer (Intel i9-12900K, GPU: GEFORCE RTX 3080, RAM: 64 GB, Santa Clara, CA, USA) was used for the analyses.

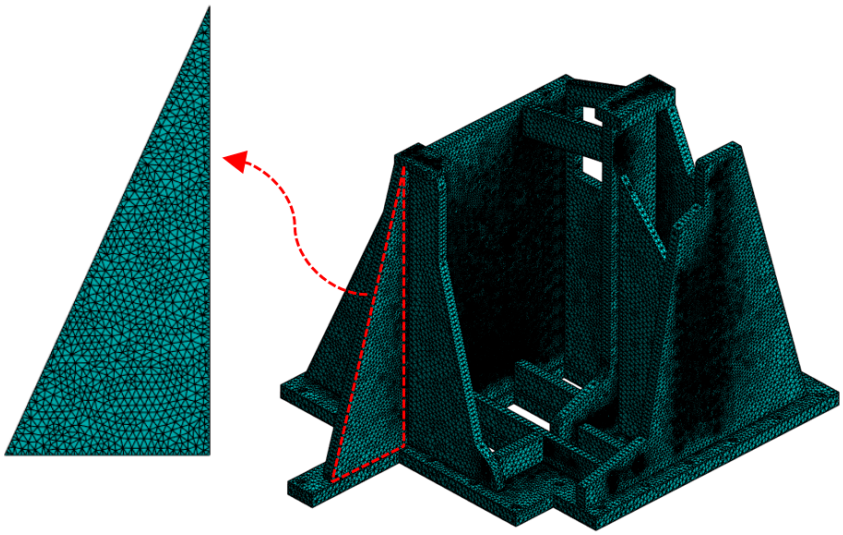


Figure 5. Finite element model of the jig.

2.3. Testing Methodology

The vibration test was conducted using a Dongling's ES-200LS2-650 vibration tester (Suzhou, China). This equipment provides a maximum impact force of 600 kN, a frequency range of 5–2100 Hz, a maximum acceleration of 1000 m/s^2 (100 g), a maximum displacement of ±76 mm, and a maximum allowable weight of 2500 kg. Acceleration measurements were recorded using Kistler's 8703A250M5 accelerometer (Winterthur, Switzerland). Data acquisition and analysis were performed using the VR9500 Vibration Controller along with the VibrationVIEW software (v.15.2, Vibration Research, Jenison, MI, USA). The test was conducted over a frequency range of 30 Hz to 700 Hz, which is set to be more than twice the minimum criterion for the first natural frequency of the vibration test jig (350 Hz). In addition, the vibration test was conducted along a single axis in the *X*-axis direction [27,28].

Figure 6 shows the jig fixing position and the position where the acceleration sensor is attached in the vibration experiment. The test subject was the headlamp vibration test jig, with a total weight of 70.4 kg for the jig and bolts combined. Sensors were fixed using adhesive to the lamp-fastening position (Top Head) at the topmost part of the vibration test jig (Figure 6). The sensors were positioned at the topmost part of the vibration test jig (Top Head) to sensitively reflect the overall vibration characteristics of the structure. This is because the top section experiences the maximum deformation and acceleration during resonance, making it the optimal location for analyzing natural frequencies and mode shapes [29]. The jig was made of ALDC material, and the test subject was fastened using M6 standard tapped bolts. The jig was secured to the vibration tester using M10 standard hex wrench-tapped bolts, with the fixed location set at the center of the top plate of the vibration tester. The test results derived the first natural frequency by analyzing changes in acceleration and phase angle. Resonance frequency was considered to occur when the change in phase angle exceeded 90°.

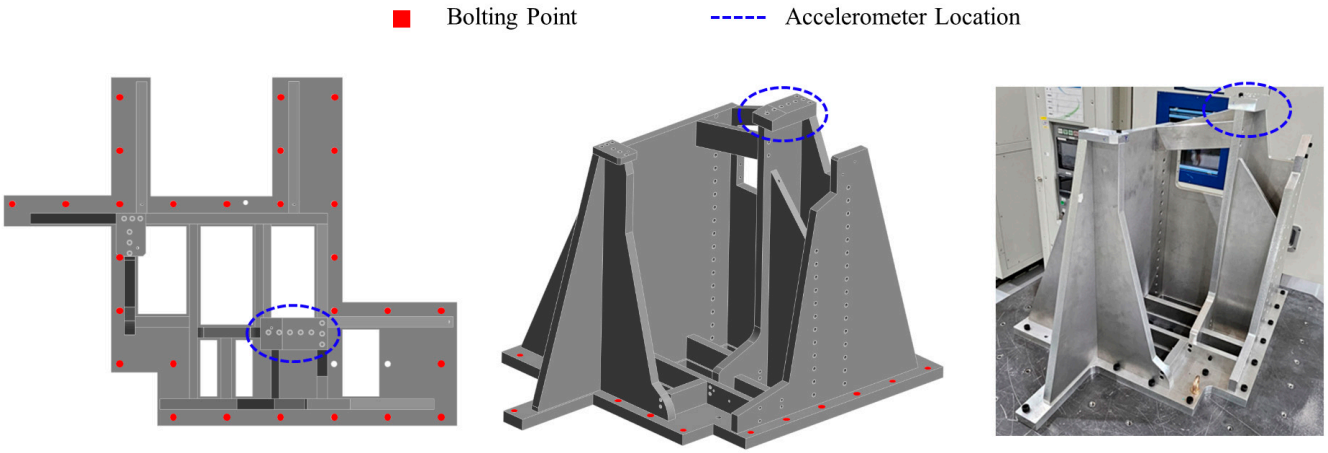


Figure 6. Vibration testing equipment and jig: (**a**) top view, (**b**) isometric view (analysis model), (**c**) isometric view (experimental model).

2.4. Comparison of Analysis and Test Results

This study was conducted to identify the optimal bolt connection method by comparing the natural frequencies and mode shapes observed in the jig for various bolt connection methods against vibration test results. The comparison was conducted by evaluating the representativeness of the bonded connection method in vibration testing. It involved analyzing changes in the jig's natural frequencies and mode shapes depending on the connection method, assessing the similarity with test results, and performing an efficiency analysis.

First, the study evaluated whether the bonded connection method, which is the most common method used to represent bolt connections, effectively represents vibration testing. For this purpose, the jig's natural frequencies derived from vibration testing were compared with those obtained through bonded-based vibration analysis. Here, natural frequency refers to the frequency at which resonance occurs at the Top Head of the jig (493.2 Hz).

Second, the study analyzed whether there were similarities or differences in the jig's natural frequencies and mode shapes depending on the bolt connection method. For this analysis, the first natural frequencies and mode shapes of the jig were compared for each bolt connection method [12,30,31]. The first natural frequency is the most sensitive indicator of structural stiffness and directly reflects changes in bonding strength and stiffness caused by different connection methods. Additionally, the first natural frequency represents the overall dynamic characteristics of the structure and serves as a critical criterion in design and analysis [32–34].

Third, the bolt connection method that produces natural frequencies most similar to those of the vibration test was determined. For this, the natural frequencies of the Top Head measured during vibration testing were compared with those calculated for each bolt connection method. Through this comparison, the connection method showing natural frequencies closest to the test results was selected.

Fourth, the efficiency of the analysis for each bolt connection method was compared. For this purpose, the CP Time and total memory usage required for the analysis of each connection method were analyzed. CP Time represents the total processing time the CPU spends on actual computation during the analysis and reflects the complexity of an analysis model and the efficiency of computational tasks. The total memory usage serves as a metric to assess the complexity and resource consumption of the analysis model. High memory requirements can slow down the analysis or even cause it to fail, making memory usage an important metric. Additionally, the time and effort required for generating finite element

models of bolts and the fastening procedures during preprocessing were also analyzed to comprehensively evaluate the usability of each connection method.

3. Results

Figure 7 shows the changes in acceleration and phase angle measured in the jig during the vibration test. The first natural frequency of the jig is 493.2 Hz, with an acceleration peak of 17.1 g and a phase angle change of 85° at this frequency. This result varied significantly from the analysis result of the bonded connection method. The natural frequency of the jig with the bonded connection method was 544.1 Hz, approximately 10.3% higher than the vibration test result.

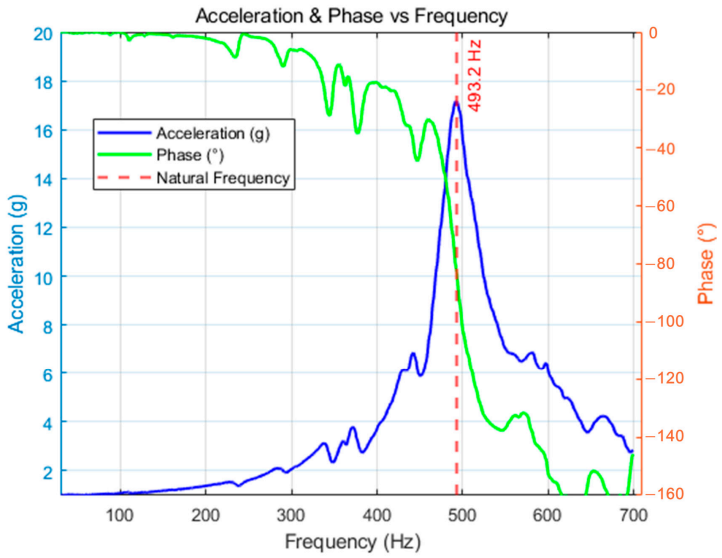


Figure 7. Acceleration and phase response with natural frequency identification.

Figure 8 shows the natural frequencies and mode shapes observed in the first mode for different bolt connection methods. The colors in Figures 8 and 9 indicate the relative mode shape deformations across the structure. Four methods (adaptive bonded, beam, screw, joint) exhibited lower natural frequencies and distinct mode shapes compared to the bonded connection method. For example, the adaptive bonded method showed a local bending mode (Local Mode) along the *y*-axis in the ribs, with a natural frequency of 324.7 Hz. The beam method also exhibited local bending along the *y*-axis in the ribs, with the lowest natural frequency of 301.8 Hz. The screw method showed local bending in the ribs, with a natural frequency of 388.2 Hz. The joint method exhibited bending deformation along the *x*-axis at the Top Head, with a natural frequency of 500.8 Hz. By contrast, the fixed bolt method showed a higher natural frequency (881.9 Hz) compared to the bonded connection method, with a local mode displaying bending along the *y*-axis in specific ribs.

Figure 9 illustrates the mode shapes and natural frequencies observed at the Top Head for different bolt connection methods. The Top Head position was specifically selected because it corresponds to the location where the accelerometer sensor was attached during the vibration test. This verifies that the analysis aligns with the actual experiment setup. The bolt connection method with the highest frequency was the bonded connection method, which exhibited a frequency of 544.1 Hz in the first mode. The method with the lowest frequency was the beam connection method, which showed a frequency of 349.8 Hz in the fifth mode. However, the bolt connection method with results most similar to those of the vibration test was the joint connection method, which exhibited a frequency of 500.8 Hz in the first mode, showing only a 7.6 Hz difference from the test result. The fixed bolt

connection method, which exhibited the highest frequency in the first mode, did not show a mode occurring at the Top Head among the six modes analyzed.

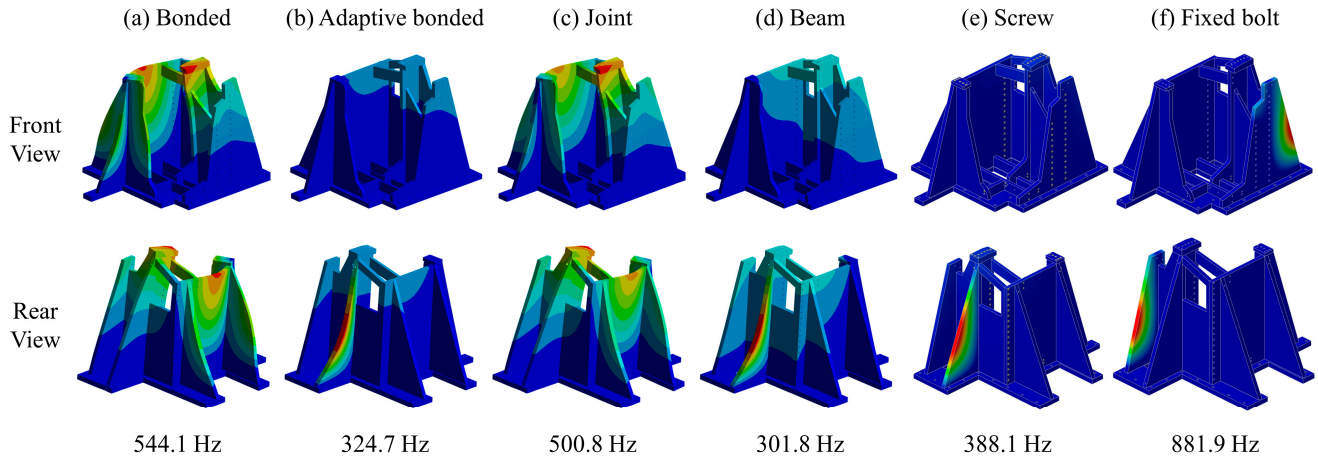


Figure 8. Natural frequencies and mode shapes based on different bolt connection methods: First mode.

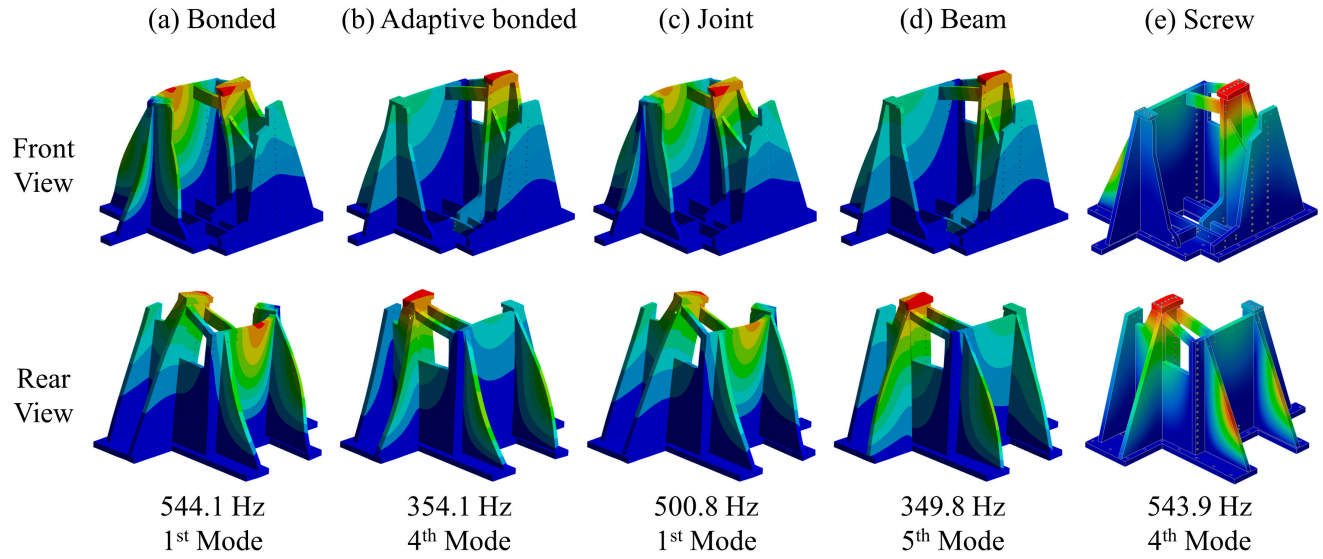


Figure 9. Natural frequencies and mode shapes based on different bolt connection methods: Top Head mode.

Table 2 summarizes the preprocessing time, CP Time, and memory usage for each bolt connection method. Preprocessing times were averaged over five trials conducted by experts to enhance the reliability of the analysis. The analysis efficiency and resource consumption varied significantly depending on the bolt connection method. Preprocessing time was particularly influenced by the number of bolts created and fastened. The adaptive bonded and joint methods required the longest times, each exceeding 6000 s (more than one hour), whereas the bonded, screw, and fixed bolt methods completed preprocessing in just 30 s. The beam method showed intermediate results, requiring approximately 3000 s. For CP Time, the adaptive bonded method took the longest, at 598 s, while the bonded method was the fastest, at 91.65 s. In terms of memory usage, the bonded method consumed the most memory at 37,393 MB, whereas the screw method was the most efficient, using only 25,590 MB.

Table 2. Comparison of preprocessing time, analysis time, and memory usage for different bolt connection methods.

	Bonded	Adaptive Bonded	Joint	Beam	Screw	Fixed Bolt
Average time required preprocessing [s]	30	6000	6000	3000	30	30
CP Time [s]	95	598	97	345	209	274
Memory usage [MB]	37,393	35,731	32,671	30,044	25,590	25,985

4. Discussion

This study analyzed the natural frequencies, mode shapes, and efficiency of various bolt implementation methods in a vibration test jig to propose the optimal connection method. To this end, the natural frequency and mode shape of the vibration test jig applied with six-bolt connection methods were compared to the natural frequency (493.2 Hz) derived from the Top Head in an actual vibration experiment. The joint connection method was found to produce the results most similar to the vibration test, with a difference of only 7.6 Hz, indicating high accuracy.

Through the results of this study, the discrepancy between vibration test results and bonded connection analysis was quantitatively assessed. The bonded connection method showed a natural frequency of 544.1 Hz, approximately 10.3% higher than the vibration test result (493.2 Hz). This is because the bonded contact exhibits greater stiffness than the bolt connections. Whereas bolt connections only connect specific points with gaps between joint surfaces, bonded connection assumes complete bonding between nodes, resulting in stronger coupling [35]. Therefore, although the bonded connection method is effective for simulating welded connections, it has limitations in representing the dynamic characteristics of bolt connections.

To determine whether the proposed bolt connection methods could simulate actual bolts, the differences in natural frequencies among the connection methods were examined. The two types of connections differed in structural stiffness, with bolt connection methods (except for fixed bolts) exhibiting relatively lower natural frequencies than bonded connections. This is because, unlike bonded connections, bolt connection methods involve smaller contact areas and account for nonlinear behavior in their coupling characteristics [36]. Additionally, the fixed bolt method exhibited a natural frequency of 881.9 Hz, which was 337.8 Hz higher than the natural frequency of 544.1 Hz for the bonded connection. This is because the fixed bolt method was based on Inspire's functionality, which treats the bolt head and endpoints of the threads as fixed points, restricting displacement and rotation degrees of freedom at both points. In other words, the fixed bolt method exhibits excessive rigidity, making it unsuitable for reproducing the dynamic characteristics of actual bolts. However, the fixed bolt method can be effectively utilized in designs requiring maximum structural coupling rigidity, such as heavy equipment, bridge structures, or stationary machinery.

A comparison of the modes among the analyzed bolt connection methods showed that the bonded connection method exhibited a global mode where the entire jig moved, while the bolt connection methods (except for the joint method) showed local modes with maximum deformation occurring in the ribs. This is because bolt connection methods have insufficient contact area and bonding strength, with nonlinear behavior influencing vibration characteristics [37–39]. On the other hand, the joint method, similar to the bonded connection, exhibited a global mode where the entire jig moved. This is because the joint method, based on ANSYS's joint functionality, rigidly connects two surfaces or points, providing high contact stiffness. As a result, relatively high contact stiffness in the rib connections occurs, effectively dispersing vibrations in local areas. Therefore, the

joint method provides higher contact stiffness than other bolt implementation methods, significantly impacting structural stiffness and vibration behavior.

This study successfully identified a reliable bolt connection method for vibration test jigs through computational modal analysis and experimental validation, providing an approach for accurate dynamic behavior prediction. The modal analysis evaluated the dynamic behavior of the structure based on natural frequencies and mode shapes. Among the methods, the joint method indicated the most similar results, with approximately a 1.5% difference from the experimental values. These results are consistent with bolt connections for the dynamic analyses of an automotive engine [22], where a similar joint method showed a high correlation between the natural frequency of the computational analysis results and experimental results, further validating the reliability of this study. Furthermore, incorporating dynamic stress into this study's methodology could lead to a more refined design of structural dynamic behavior. A study on FE refinement for accurate dynamic stress [40] showed that considering dynamic stress in the evaluation process not only improved the structure's fatigue performance but also enhanced the reliability of the design under dynamic conditions. Thus, this approach could provide dynamic characteristic-based designs with greater practical applicability and improved overall performance.

In terms of analysis efficiency, notable differences between the connection methods were observed. The adaptive bonded method required the longest analysis time at 598 s, followed by the beam method at 345 s, while the joint method required a relatively short analysis time of 97 s. The screw and fixed bolt methods had analysis times ranging from approximately 200 to 300 s. The bonded method required the shortest analysis time at 91.65 s, but exhibited significant discrepancies from the test results, limiting its ability to reproduce the dynamic characteristics of actual structures. During preprocessing, the joint and adaptive bonded methods required approximately 2 min per bolt to generate line bodies and assign contact conditions, and the beam method also required significant time for assigning contact conditions, resulting in low preprocessing efficiency. By contrast, the screw and fixed bolt methods significantly reduced preprocessing time by utilizing Inspire's Fastener functionality, which automates preprocessing. As a result, while the joint method provided high analysis accuracy, it required substantial time for preprocessing, making it the second most time-consuming method overall. The adaptive bonded and beam methods also required significant time for both preprocessing and analysis, whereas the screw and fixed bolt methods demonstrated their potential as efficient alternatives in the early stages of design owing to their simplified preprocessing and short analysis times.

This study has some limitations. First, the analysis did not explicitly consider bolt preload and contact friction coefficients, indicating that the subtle effects that may occur under actual bolt fastening conditions were not fully captured. Second, the experiment was limited to excitation in the x-axis direction only, restricting a comprehensive evaluation of the dynamic behavior of the structure under various vibration directions. Third, the study was based on a single jig design case, limiting the generalizability of the findings to other structural designs. Nevertheless, this study demonstrated the utility of quantitatively comparing natural frequencies and mode shapes for various bolt implementation methods, providing valuable insights for the design and analysis of vibration test jigs.

5. Conclusions

This research systematically compared and analyzed the natural frequencies and mode shapes associated with different bolt implementation methods in the design of vibration test jigs. The bonded condition failed to adequately reproduce the dynamic characteristics of bolt connections, resulting in significant discrepancies between the analysis and actual vibration test results. However, the joint method exhibited the smallest difference in natural

frequency compared to the test results, making it a reliable option for design. This suggests that the joint method can relatively accurately represent the contact conditions and stiffness of actual bolts, thus demonstrating that the choice of bolt connection method has a critical influence on the accuracy and efficiency of design and analysis. Although there were some differences between the analysis models and experiments, along with limitations in achieving complete consistency across software platforms, this study provides practical guidelines for selecting connection methods to consider during the early design stage. We believe that future studies incorporating diverse loading conditions and additional design cases will help in establishing more generalized criteria.

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Conflicts of Interest: Author Ji Hye Kang was employed by the company SL Corporation. The remaining authors declare that the re-search was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Figure A1 shows an image of one rib in the finite element model of the jig with varying mesh sizes. To achieve a balance between efficiency and reliability, the mesh sizes were varied throughout the analysis. Detailed information for mesh sizes ranging from 8 mm to 4 mm is provided in Table A1. Additionally, Table A1 presents the number of nodes and elements, as well as the mesh quality, for each mesh size. The mesh quality was compared using the aspect ratio, which shows convergent values at a mesh size of 5 mm. Based on this evaluation, the mesh size for the jig model was set to 5 mm.



Figure A1. FE models of ribs according to mesh size.

Table A1. Number of nodes and elements and mesh quality according to mesh size.

Mesh Size [mm]	8	7	6	5	4
Number of Nodes	608,064	867,557	1,015,244	1,094,136	1,425,119
Number of Elements	343,811	496,721	582,436	627,725	820,739
Aspect Ratio	2.69	2.50	2.43	2.31	2.29
Jacobian Ratio	0.97	0.96	0.97	0.97	0.97
1st Frequency [Hz]	544.9	543.5	543.7	543.8	543.8

Appendix B

Table A2. Effect of Bolt Mesh Size on the First Natural Frequency.

Mesh Size [mm]	7	6	5	4	3	2
1st Frequency [Hz]	500.14	500.14	500.12	500.12	499.97	499.96

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