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Vibration Simulation of Structural Members Bolted with CFRP

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In recent years, the transportation industry has prioritized reducing CO_2 emissions through vehicle weight reduction to mitigate environmental impacts. Consequently, the adoption of "multi-material structures" that strategically combine materials such as aluminum alloys and Carbon Fiber Reinforced Plastic (CFRP) within vehicle frames has become increasingly prevalent. CFRP is particularly valued for its exceptional specific strength and the ability to tailor mechanical properties by optimizing fiber orientation. While mechanical joining through bolting is widely utilized for CFRP due to its high reliability and re-assemblability, existing research has primarily focused on characteristic failure modes. This has left a significant gap in understanding the dynamic behavior and vibration characteristics of these bolted assemblies.

This study proposes a novel numerical simulation methodology to predict the natural frequency of bolted CFRP structural members relative to their tightening force. The core of the method involves inserting "interface elements" at the contact surfaces within a finite element model. These elements are defined as massless orthotropic elastic layers whose characteristics are determined using a simplified mechanical model based on interface tribology, incorporating surface texture parameters. This approach effectively reproduces the complex influence of the interface's contact state on the global natural frequency. Furthermore, the inherent anisotropy of CFRP was incorporated by assigning bulk anisotropic material properties to the solid elements, ensuring an accurate representation of directional stiffness.

To verify the effectiveness of the proposed simulation method, a series of impact tests were conducted, and the experimental results were compared with numerical values. Initially, a fundamental comparison was made between an "assembled specimen," consisting of two bolted CFRP plates, and a "monolithic specimen," a single-plate structure of the same dimensions. This investigation clarified the influence of the joining interface and its contact state on the natural frequency. The results confirmed that by introducing interface elements utilizing the material properties of the matrix resin alone, analytical accuracy equivalent to that of the monolithic specimen could be achieved across varying clamping forces.

Subsequently, the versatility of the proposed method was evaluated across three distinct material combinations: aluminum alloy joined with CFRP, CFRP plates with identical fiber orientations, and CFRP plates with different fiber orientations. The relationship between the average clamping force and the natural frequency was analyzed for each configuration. In all patterns, the analytical values showed excellent agreement with the experimental data, accurately capturing frequency shifts associated with increasing bolt tension and the resulting saturation of contact stiffness. Notably, the accuracy achieved was comparable to that of a conventional aluminum-to-aluminum (Al-Al) joint used as a reference.

The findings demonstrate that the proposed simulation method, integrating simplified mechanical models into interface elements, is highly effective for the vibration analysis of bolted CFRP structures. The consistency between results across various material combinations suggests that this approach possesses broad versatility. It is concluded that the proposed method is widely applicable to the structural design and NVH optimization of bolted joint components in modern multi-material vehicle architectures.

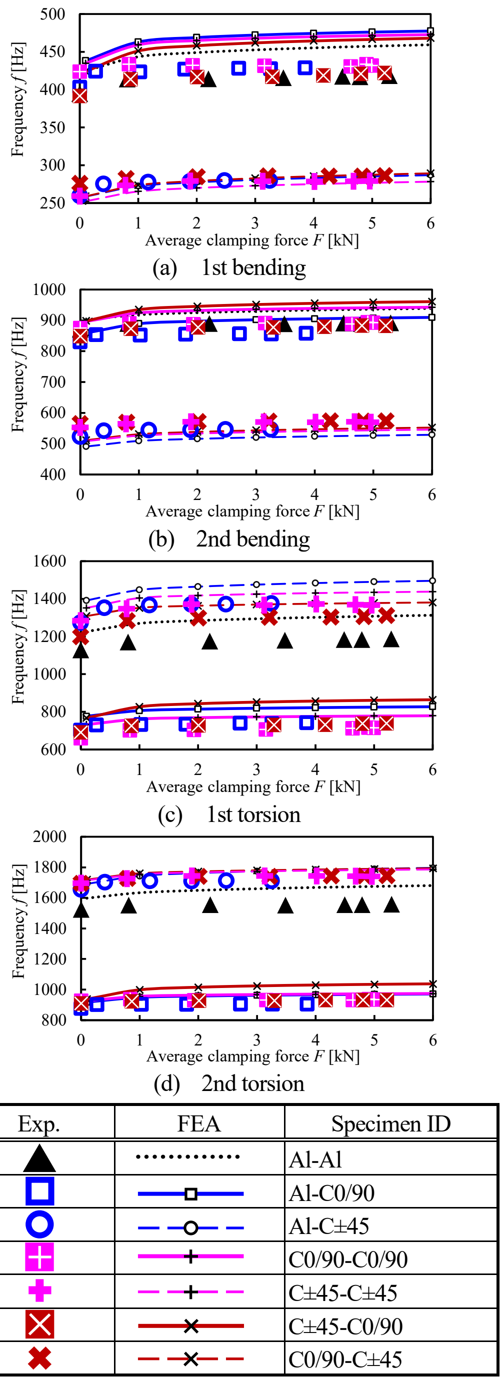

Fig.9 Relationship between average clamping force and natural frequency