Numerical Simulation and Experiment for Driving Interference-Fit Fastener Process with Stress Wave Method

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Abstract: Interference-fit fasteners are commonly used in aircraft structures and the quality of their installation is critical to the service life of the structures. Conventional installation methods of driving fasteners usually use pneumatic or hydraulic tooling as a driving force, which can cause significant installation damage when a large driving force is required. This paper presents numerical simulation and experimental approaches for investigating the process of driving interference-fit fasteners with a stress wave installation method. The performance and advantages of the stress wave installation method are explored using the finite element method. In particular, the loading characteristics and driving process of the new method are investigated and compared with conventional installation methods. The results indicate that the stress wave method can effectively drive fasteners with higher interference values and cause much less damage than conventional installation methods. Fatigue testing for fasteners installed by both conventional methods and the stress wave method is carried out to verify the results from numerical simulation. The stress wave driving method can also increase the fatigue strength of the joint. This paper review highlights the developments of stress wave installation methods and their numerical simulation algorithms as well as fatigue testing approaches.

Keywords: Interference-fit, fastener, driving force, stress wave, finite element method.

1. INTRODUCTION

Over recent years interference-fit joining technology including the application of stress wave methods has become important in the achievement of long service life, high reliability and low maintenance cost of aerospace joint structures. Most results in the area of stress wave method have been patented recently. For example, Cao developed a stress wave install apparatuses for interference-fit fastener installation [1]; a distributed stress wave analysis system was presented for detecting structure borne sounds caused by friction [2]; A sensor specifically was disclosed for detecting stress waves for use in a stress wave analysis system [3,4]; and a statistical process, and system for implementing the process, was developed for the analysis of stress waves generated in operating machinery or equipment [5]. For research work in interference-fit joining technology, Heller and Carey [6] developed a special finite element model for stress analysis of interference-fit fasteners. Nurse et al. [7] and Ball [8] used transmission and reflection photoelasticity to determine stress intensity factors for artificial cracks at fastener holes with an interference-fit pin. Rufin [9] presented a cold expansion insertion technique for reinforcing fastener holes that might be sensitive to damage from repeated fastener installation and removal. Duprat et al. [10] presented a method for estimating the fatigue life of interference-fit fasteners. The method is based on the determination of local stress using the finite element method and on a multiaxial fatigue model. Stefanescu et al. [11] investigated the effect of preexisting cracks on the residual stress field produced by cold expanding a fastener hole, and on subsequent fatigue crack growth. Cobb et al. [12] examined the effect of transducer placement on the sensitivity of the energy ratio algorithm in a structural health monitoring system for providing early detection of fatigue cracks initiating from fastener holes. Recently, Cao and Qin [13] and Cao and Li [14] developed a stress wave driving method that can significantly increase the installation quality of fastener structures and is beneficial to improve fatigue strength. It should be emphasized that the interference-fit joint can achieve much greater fatigue strength of metal joints than conventional joint methods [10]. In fact, interference-fit fasteners are commonly used in aircraft and automotive structures. In particular, they are extensively used in the main forced components of F-16, F-15, LAVI, and B-737 aircraft, for example in the girders of front fuselages, many joints and opposite-joining girders of aerofoils. Moreover, thousands of interference-fit lockbolts are used in the manufacture of each Chinese J10.

Conventional installation methods drive fasteners into apertures (holes) using pneumatic or hydraulic tooling. Installation damage is most likely to be induced using these methods, and they are ineffective when driving fasteners with relatively high interference values. Driving fasteners using a stress wave can effectively increase installation quality [13,14], which has already been used in aircraft manufacture, e.g. in the B-747 [15].

In this paper, the applicability, effectiveness and advantages of the stress wave method are assessed using
both simulations by the finite element method, and a purely experimental approach. The installation quality of the stress wave method is compared with that of conventional installation methods. This paper illustrates a recent patent presented by Cao and Sheng [1] and comparison is made numerically between the technique described in [1] and conventional installation techniques.

2. PRINCIPLE OF DRIVING FASTENERS USING A STRESS WAVE

Most existing installation methods drive fasteners into an aperture using pneumatic or hydraulic tooling, the so-called forced-installation methods. The shortcomings of forced installation are: (1) it requires a large driving force when the interference value is high, which makes it difficult to drive the fastener into the aperture; (2) hammering methods can easily cause damage to the aperture wall when driving fasteners with a high interference value. A large hydraulic cylinder apparatus can be used if there is sufficient space to provide the necessary operating clearance, but many aircraft structures afford limited space. Existing forced-installation methods are effective only when the interference value is very small. The interference value of interference-fit bolts used in most transport aircraft is only 0.05%-0.35% of the diameter for a diameter of 8mm and 0.04%-0.28% of the diameter for a diameter of 10mm [16]. To prevent or reduce damage to structures during installation, fasteners with high interference values and thick sandwich structures are always frozen before installation, and the driving technology required is usually very complex.

Stress waves in structures are a form of elastic energy propagation. When a solid material is acted upon by a force for a very short period of time, the disturbance caused by the force travels in the material in the form of a time-dependent deformation wave, whereby one says that a stress wave propagates in the solid [17]. The stress wave will reflect when it travels across interfaces between two different materials. According to stress wave theory, when an elastically compressive wave propagates along a finite length rod (here a fastener), it will change into a tension wave after reflecting from the remote or free end of the fastener, while its waveform remains unchanged. Due to the Poisson effect, a contraction of the fastener will occur perpendicular to the direction of propagation. Therefore, an elastic tension wave at the remote end of the fastener will be produced when the fastener is driven using the stress wave method. The tension wave will cause contraction of the fastener in the radial direction and a decrease of its diameter. As a result, the fastener is easily installed. The stress wave device used for driving interference-fit fasteners is illustrated in Fig. (1).

3. NUMERICAL SIMULATION OF FASTENING PROCESS

To explore the performance and advantages of the stress wave method, the process of fastening interference-fit fasteners using that method is numerically simulated using the finite element analysis software ABAQUS [18], and the result is compared with that from a conventional installation method. The loading process in the conventional hydraulic method is thus completed utilizing the ABAQUS/Standard module [18], a general analysis module that is widely used across a range of engineering problems, both linear and nonlinear, such as static problems, dynamic problems, heat transfer in structures, electrostatic response problems, and so on. The stress wave method is viewed as a dynamic loading process, and its simulation is performed with the ABAQUS/Explicit module [18]. Explicit dynamic finite element analysis is a module that can simulate the dynamic response of a structure under the action of impact loads or transient loads, contact-impact problems and explosion problems, for example.

Fig. (1). Schematic representation of stress wave device: 1 power supply 2 SCR (silicon controlled rectifier) 3 recharge switch 4 capacitor bank 5 discharge switch 6 shock absorber 7 electromagnetic coil 8 drive coil 9 conditioner 10 fastener 11 and 12 stack panels.

Due to symmetry of the structure, the solution domain and the element mesh used shown in Fig. (2) are used. The element CAX4R defined in ABAQUS [18] with induced integration is used to reduce computing time and to prevent or reduce the possibility of hourglassing modes.

Fig. (2). Geometry configuration and element mesh of the fastener.

The fastener used is a titanium alloy lockbolt with diameter 6 mm, and the tack material is 7050T7452 aluminum alloy with thickness 3mm for each layer. A series of experiments were conducted by the authors to obtain the property parameters of the material of the titanium alloy lockbolt. Considering that (a) the titanium alloy is sensitive
to strain rate and (b) the structural loading is a dynamic process in the wave stress method, the experiment for obtaining the dynamic property parameters of the titanium alloy material was performed using Split Hopkinson Pressure Bar equipment. The mechanical properties of 7050 T7452 aluminum alloy can be found from literature [16,19] and are listed in Table 1, where $E$ is Young’s modulus, $\mu$ Poisson’s ratio, $\rho$ the mass density, and $\sigma_b$ the strength of materials. In the following numerical simulation both the hydraulic driving process and the stress wave driving process are presented, and the results are used for performance analysis in Section 4.

Table 1. Static Mechanical Characteristics of Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$E$ (MPa)</th>
<th>$\mu$</th>
<th>$\rho$ (kg/mm$^3$)</th>
<th>$\sigma_b$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium Alloy Lockbolt</td>
<td>110000</td>
<td>0.30</td>
<td>0.00484</td>
<td>1123</td>
</tr>
<tr>
<td>7050T7452 Aluminum Alloy</td>
<td>68500</td>
<td>0.35</td>
<td>0.00283</td>
<td>540</td>
</tr>
</tbody>
</table>

3.1. Numerical Simulation of the Hydraulic Driving Process

The simulation of the hydraulic driving process was conducted using the finite element software ABAQUS. The element mesh used is shown in Fig. (2). Fig. (3) presents local enlargement of the area around the corner of the fastener. Stresses and strains of the structure are calculated for a series of interference values. The simulation results indicate that the mesh is significantly distorted if the interference value is greater than 1.1%. Therefore the value of 1.1% can be viewed as a critical value, and the interference value used in the hydraulic method should be less than or equal to 1.1%. The results for the Von Mises stress are shown in Fig. (4) and listed in Table 2, and are then analyzed in Section 4.

Fig. (3). Local enlargement of the element mesh.

It can be seen from Table 2 that the residual stress of the stack panel and the fastener increases along with an increase in the interference value, as expected.

Fig. (4). Von Mises stress versus interference value in hydraulic method.

(a) 1.1% interference value  (b) 0.8% interference value  (c) 0.5% interference value
3.2. Numerical Simulation of Stress Wave Driving Process

The same mesh as in Section 3.1 is used for simulating the driving process using stress waves. The simulation analysis was performed using the same ABAQUS 6.8 software. The results for stress and strain of the structure as a function of the interference value are listed in Fig. (5) and Table 3, and are also used in Section 4. From the simulation results, the upper limit of the interference value is found to be 2.8% using the stress wave method. Note that if the interference value exceeds 2.8% the material of the fastener will experience plastic deformation.

It can again be seen from Table 3 that the residual stress of the stack panel and the fastener increases as the interference value increases.

4. ANALYSIS OF SIMULATION RESULTS

To investigate the performance of the stress wave method, Fig. (6) presents the distribution of Von Mises stress for both hydraulic method and stress wave method when the interference values are at their maximum.

As indicated in Section 3.1, in the hydraulic method the upper limit of the interference value is about 1.1%. Checking the stack material after the driving process, it is found that the bolt is in contact with the stack panel and there is a stress concentration near the contact area. The stress there can reach the ultimate strength of the material which is about 530–540MPa (as shown in the left of Fig. 6a). The area where the stress displays in the red in Fig. (6a) means that the stress is about 450–486MPa, and the maximum stress is found at the lower left point of the material. The peak stress in the fastener is 423.1MPa, which occurs near the central line. The area where the stress is in the blue in Fig. (6a) means that the stress is about 370–423MPa. The measurement after the driving process shows that the downward displacement of the lower left point of the stack material is 0.026mm.

![Von Mises stress distribution](image)

(a) 2.8% interference value  
(b) 2.2% interference value  
(c) 1.6% interference value

**Fig. (5).** Von Mises stress versus interference value in stress wave method.

<table>
<thead>
<tr>
<th>Interference Value</th>
<th>Maximum Residual Stress of Stack Panel</th>
<th>Displacement in y Direction of Lower Left Point of Stack Panel</th>
<th>Maximum Residual Stress of Fastener</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5%</td>
<td>359.2MPa</td>
<td>0.007mm</td>
<td>217.8MPa</td>
</tr>
<tr>
<td>0.8%</td>
<td>485.4MPa</td>
<td>0.0145mm</td>
<td>335.6MPa</td>
</tr>
<tr>
<td>1.1%</td>
<td>540MPa</td>
<td>0.026mm</td>
<td>423.1MPa</td>
</tr>
</tbody>
</table>
Driving Interference-Fit Fastener Process with Stress Wave Method

In contrast, with the stress wave method the upper limit of the interference value is about 2.8%. The maximum residual stress of the stack material after the driving process is found at the lower left point of the material, which is as high as 522Mpa, and thus part of the material is in a plastic state (as shown on the left of Fig. 6b). The maximum stress (it is shown in the red color in Fig. 6b) exists in a small area close to the contact interface. The stress level in that small area is about 460–486Mpa (as shown in the black box in Fig. 6b). The maximum stress in the fastener is 625.6MPa and the stress value in the yellow areas is 420–570MPa. The measurement after the driving process shows that the downward displacement of the lower left point of the stack material is 0.026mm.

With the hydraulic force driving method, there is almost the same distribution of residual stress in both the upper and lower stack interlayers. The region where the residual stress is above 90% of the yield stress is located within 1.2mm around the bolt. In contrast, in the stress wave driving method, the distribution of residual stress in the upper layer is significantly different from that in the lower layer of the stack material. The only region where the residual stress is above 90% of the yield stress in the lower layer of the stack material is more than 3mm from the outer surface of the bolt. Thus with the stress wave driving method the region with residual stress is larger than that from the hydraulic force driving method, a feature that can increase the fatigue strength of the structure.

It can be seen from the analysis above that a higher interference value can be implemented using the stress wave method than by conventional methods. On the average, the optimum interference value of aluminum alloy is in the range of 3–5% and that of steel alloy is about 2% [20]. The permitted interference value using traditional installation methods is far lower than the optimum interference. In contrast, the stress wave driving method can be used to install fasteners with interference values as high as 3%, which can satisfy their optimum interference value. Fig. (7) illustrates geometric configuration of HST10 lockbolts used in stress wave method.

5. FATIGUE EXPERIMENT

To verify the results and analyses in Sections 3 and 4, experiments were conducted to ascertain the structural fatigue life of fasteners processed by both conventional method and the stress wave method. The testing specimen consists of four bolts under unidirectional shear condition and two 7050 T7451 aluminum alloy stacks. The two plates have equal thickness of 4.8mm as shown in Fig. (8). The periodic load is constant in amplitude and is in the form of the sine function. The maximum temperature was kept below 65 °C. We employed a joint material that can transfer loads much greater than the value tested. The ratio of maximum stress to minimum stress is taken to be 0.1 and a PLG-50 Micro-computer Controlled High-Frequency Fatigue Testing Machine was used to conduct the experiments. The measurement results are shown in Table 4, where $R_{max}$ stands for the maximum load applied and $R_{min}$ represents the applied minimum load.

It can be seen from Table 4 that the fatigue life of the joint structure is much higher using the stress wave method than that using a conventional installation method.

6. CONCLUSIONS

In this paper, numerical simulation and corresponding fatigue experiments are conducted to investigate the mechanical performance of fastener structures installed by either a conventional method or the stress wave method. The following conclusions can be drawn:

<table>
<thead>
<tr>
<th>Interference</th>
<th>Maximum Residual Stress of Stack Panel</th>
<th>Displacement in y Direction of Lower Left Point of Stack Panel</th>
<th>Maximum Residual Stress of Fastener</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6%</td>
<td>523.4MPa</td>
<td>0.044mm</td>
<td>515.7MPa</td>
</tr>
<tr>
<td>2.2%</td>
<td>520.9MPa</td>
<td>0.097mm</td>
<td>574.0MPa</td>
</tr>
<tr>
<td>2.8%</td>
<td>522.0MPa</td>
<td>0.187mm</td>
<td>625.6MPa</td>
</tr>
</tbody>
</table>

(a) hydraulic method  (b) Stress wave method
1) The maximum interference value allowed by the stress wave driving approach is much greater than that of the hydraulic force driving method, indicating that it is practical to install large interference fasteners using the stress wave method.

2) The stress concentration induced from the conventional installation method is much greater than that induced from the stress wave method.

3) The stress wave driving method can produce higher residual stress and a wider stress distribution area than conventional installation methods, thereby significantly improving the fatigue life of joint structures.

![Fig. (7). HST10 lockbolts installed using stress wave method (6mm in diameter, interference value 2.6% of the diameter).](image)

![Fig. (8). Geometry of the specimen.](image)

7. CURRENT AND FUTURE DEVELOPMENT

Future developments of the current stress wave installation method are possible. For example, more advanced numerical simulation methods including meshless methods and Trefftz finite element methods [21-23] can be developed for analyzing and designing more accurately stress wave installation set-up; and smart material technology can be applied the stress wave method enabling the function of automatic control which makes installing and its set-up to be more intelligent.

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REFERENCES


