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Fatigue Analysis of BRB Weld under Low Period and Large Deformation based on DIC Technology

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Abstract

This paper conducts an in-depth study on the fatigue performance of buckling-restrained braces (BRBs) under low-cycle large deformation conditions. As a device that utilizes the hysteretic energy dissipation of metal yielding, BRBs have been widely used in the design of new structures and the seismic strengthening of existing structures. Its remarkable advantages include stable performance, convenient fabrication, low cost, and excellent hysteretic performance. Applying DIC technology to the fatigue analysis of BRB welds under low-cycle large deformation can achieve full-field measurement of deformation and stress at the weld, providing strong technical support for in-depth study on the fatigue performance of BRB welds.

Keywords

Weld Fatigue; Low-cycle Large Deformation; Buckling-Restrained Brace.

1. Introduction

With the continuous development and innovation of modern building structures, buckling restraint bracing (BRB) has been more and more widely used in engineering as an effective seismic energy-dissipating component. BRB can effectively protect the main structure and improve the seismic performance of the structure by yielding energy under the action of earthquake and other dynamic forces. However, the fatigue performance of BRB under low cycle and large deformation is one of the key factors affecting its long-term reliability. In practical engineering, metal structures are often affected by dynamic loads, such as earthquakes, wind disasters, explosions, etc., these loads usually have the characteristics of low period and large deformation, BRB is usually made of steel, and its weld quality is directly related to the overall performance of BRB. When subjected to low-period and large deformation, fatigue damage is likely to occur at the BRB weld, thereby reducing the bearing capacity and energy dissipation performance of the BRB. Consequently, conducting fatigue analysis of BRB welds under low period and large deformation holds significant theoretical importance and engineering application value. As a non-contact optical measurement approach, digital image correlation (DIC) technology boasts advantages such as easy operation, a broad measurement range, strong anti-interference capability, high accuracy, and excellent real-time performance. In recent years, it has been widely utilized in the domains of material performance testing and structural deformation monitoring. Applying DIC technology to the fatigue analysis of BRB welds under low periodic and large deformation enables full-field measurement of deformation and stress at the weld, providing robust technical support for in-depth exploration of the fatigue properties of BRB welds. Therefore, this paper plans to employ DIC technology to analyze the fatigue properties of BRB welds under low-period large deformation and uncover the mechanical properties of BRB welds under such conditions through a combination of experimental research and numerical simulation, thus providing a scientific foundation for the design, construction, and maintenance of BRB.

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2. Background of the Research Topic

Under the action of earthquake and strong wind, the structure usually produces large nonlinear deformation, and the repair cost of the structure is high or the repair is difficult, and the reciprocating load during the large earthquake is very easy to cause the failure or destruction of the ordinary support itself and the connection, so that its economy is greatly reduced, and the energy dissipation capacity of the ordinary support after buckling becomes poor, and it is difficult to effectively consume earthquake energy. Even a larger section of support does not guarantee that buckling will be avoided under the action of strong winds and strong earthquakes. Therefore, some foreign researchers have proposed a kind of component without buckling under compression, which is called buckling-restrained braces (abbreviated as BRB) or anti-buckling braces, and they are used as dampers in high-rise building structures. Buckling restraint supports, which are currently in use and under development, can be divided into two main categories by the shape of the external restraint unit, one is tubular buckling restraint support and the other is wallplate non-buckling restraint support. Among them, tubular buckling restraint support is widely used in steel structures. A typical tubular buckling brace consists of three parts: the core member, the outer restraint element and the unbonded material. The unbonded material, also known as the sliding mechanism, is often attached to the core unit to eliminate the friction between the core element and the external restraint unit; The core unit, also known as the core material, is the main stressed member in the buckling restraint support, which is generally made of steel of specific strength, and its cross-sectional form is usually cross-shaped and slotted, in which the outer restraint unit is mainly responsible for providing lateral restraint for the whole structure to reduce or prevent the core unit from buckling. The working principle of buckling restraint support is as follows: the support plays the role of bearing the axial force generated under the seismic response in the structure, the axial force is all borne by the core material of the support center, and the peripheral restraint unit provides the bending limit of the core unit, so that the core material can yield but not buckle; The core element is coated with an unbonded coating and a narrow void is created to reduce or eliminate the force transmitted to the restraint element when the axial force is applied. Ordinary support will buckle before giving in under compression, which will lead to a sharp decrease in bearing capacity or even instability and damage, while buckling restraint support can yield without buckling regardless of tension or compression, and has good energy dissipation capacity.

Buckling restraint support initially emerged in the United States. It gradually reached maturity in Japan during the 1970s and 1990s and then spread to the United States, Canada, and Taiwan. Buckling restraint supports possess the following advantages. Firstly, they have strong energy dissipation capacity. Under seismic action, they can consume a significant amount of energy through yield deformation, thus reducing the seismic response of the main structure. Secondly, they increase structural stiffness. Compared with traditional braces, buckling restraint braces can provide higher stiffness under the same cross-sectional size, reducing the size of components and consequently lowering project costs. Thirdly, buckling restraint support is easy to install. It is generally connected to the main body by bolting or welding, and the installation process does not require complex construction equipment and technology. Moreover, it improves the mechanical performance of the structure by adjusting the internal force distribution to make the force of the structure more reasonable. Due to characteristics such as non-contact and high accuracy, this method has been widely applied in fields like structural micro-deformation measurement, stress measurement, strain measurement, and non-destructive testing. The measurement principles include the principle of digital image correlation and the principle of binocular vision measurement. When an earthquake occurs, the weld of the buckling restraint support at the welding joint is subjected to a large dynamic load,

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which is prone to cause fatigue damage and even lead to the collapse of the structure. In this case, the main failure modes of the material are high-strain and low-cycle fatigue damage and fracture. Among them, the weld joints of the transition section of the buckling restraint support are most likely to experience fatigue damage. By comparing the mechanical properties of the BRB structural weld at different angles in the one-way fatigue loading test and the fatigue performance of the weld during the reciprocating fatigue loading test, and using the full-field strain measurement technique (DIC) to observe and study the strain changes of the weld area of each specimen in the process of vibration fatigue.

Rewritten version:

Buckling restraint support first originated in the United States. Later, it achieved maturity in Japan between the 1970s and 1990s before spreading to the United States, Canada, and Taiwan. These supports offer several advantages. They possess strong energy dissipation capabilities, as they can consume a large amount of energy through yield deformation during earthquakes, thereby reducing the seismic response of the main structure. They also increase structural stiffness. Compared to traditional braces, they can provide greater stiffness under the same cross-sectional size, leading to smaller component sizes and reduced project costs. Installation of buckling restraint supports is easy, as they are typically connected to the main body by bolting or welding, without the need for complex construction equipment and technology. Additionally, they enhance the mechanical performance of the structure by adjusting the internal force distribution for a more reasonable force application. Due to features like non-contact operation and high accuracy, this method has found wide application in areas such as structural micro-deformation measurement, stress measurement, strain measurement, and non-destructive testing. The measurement principles involve the digital image correlation principle and the binocular vision measurement principle. When an earthquake strikes, the weld of the buckling restraint support at the welding joint is exposed to a significant dynamic load, which can easily cause fatigue damage and potentially lead to structural collapse. In such cases, the main failure modes of the material include high-strain and low-cycle fatigue damage and fracture. Particularly, the weld joints in the transition section of the buckling restraint support are most susceptible to fatigue damage. By comparing the mechanical properties of the BRB structural weld at different angles in the one-way fatigue loading test and the fatigue performance of the weld during the reciprocating fatigue loading test, and using the full-field strain measurement technique (DIC) to observe and study the strain changes in the weld area of each specimen during vibration fatigue.The analysis of the influence of welding residual stress on the fatigue life of specimens with welds is of practical significance for improving the industrial technology level in China. At present, the fatigue performance analysis of BRB component welds at low cycle and large deformation is relatively lacking, so it is necessary to grasp the fatigue performance of the weld joints supported by buckling constraints, in order to alleviate the problem of component failure caused by buckling restraint supports when entering the elastoplastic stage or plastic stage.

3. Current Research Status at Home and Abroad

3.1. Current Status of Fatigue Research on Metal Welds

Hua et al. (1984) carried out several two-stage amplitude cyclic load tests, and the test results showed that if only a simple linear relationship was used to calculate the fatigue damage accumulation, the calculation results were quite different from the actual results. However, the calculation results of the bilinear damage accumulation model are affected by the sequence of low load and high load. In 1991, Gong Shihong et al. conducted a comparative test on the low-period fatigue performance of 22MnSiV and ordinary steel bars under seismic loads, and finally concluded that the random fatigue test under seismic load spectrum showed that 22MnSiV had

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a high random fatigue life. Sheng Guangmin et al. in 1995 showed that under the action of strong earthquake data, the welding joints of buildings are most prone to failure after about 100 cycles under the action of strong earthquake data. In 1998, in order to explore the nature of fatigue damage, Yang Huaren carried out fatigue loading tests with different loads and different cycles on metal welds with fixed life, and the test results showed that the fatigue damage of ferrite of metal welds was characterized by the change of dislocation configuration, and the formation of subcrystals at the same time as the metal produced a large number of slip zones to form cracks. In 2000, Zhao Yongxiang et al. tested the weld specimens of stainless steel pipes with smooth surfaces according to the "effective short crack criterion", and the results showed that the effective short crack originated at the junction of ferrite and austenite matrix. In 2004, Hui Li et al. experimentally analyzed the evolution law of fatigue short cracks on the metal surface of titanium alloy welds, and the results showed that the evolution law of fatigue short cracks on the metal surface of titanium alloy welds can be described by fractal dimension. In 2003, Qin Bin et al. conducted experimental studies on the high strain and low periodic fatigue properties of different specifications of 20MnSiVHRB400 steel bars, and determined that the cyclic response characteristics of two specifications of 20MnSiVIII steel bars were mainly cyclic stability.

In 2011, Lin Zhenye and others conducted low-cycle fatigue repeated load tests on hot-rolled H-beam beams. They reached the conclusion that hot-rolled H-beams possess excellent seismic performance, being close to that of Q345B hot-rolled H-beams. In 2014, Zheng Jialiang and others tested the high-strain and low-cycle fatigue performance of the HRB500E steel bar under constant strain conditions to simulate the failure mode of the steel bar under seismic action. In 2015, Luo Yunrong and others employed the axial strain control method to study the low-cycle fatigue performance of the HRB400III-grade steel bar and obtained the low-cycle fatigue life prediction formula of the steel bar under low strain amplitude. This formula is in good agreement with the test results and provides a basis for the low-cycle fatigue analysis, damage assessment, and life prediction of this steel grade. In 2018, Jiang Congxiao and others carried out the same amplitude high strain and low-cycle fatigue test on different forms of Q345 flat plate butt welded components. The test results indicated that the low-cycle fatigue performance of automatic welds is better than that of manual welds. Moreover, the number of low-cycle fatigue loading turns would significantly affect the strain value of the weld area of the specimen. Eventually, weld failure would lead to the failure of the specimen. In 2020, Yu Suting et al. carried out laser welding of aluminum alloy specimens, and used a full-field strain gauge to measure the change of the principal strain during the welding process, and concluded through comparative tests that the greater the welding residual stress of the specimen, the greater the fatigue damage in the weld area, and the faster the vibration fatigue damage of the specimen. The vibration fatigue life of each specimen under different welding residual stresses was calculated by finite element software analysis. In 2022, Zhang Hao simulated the cyclic loading of the double weld structure through finite element software, and obtained the surface crack initiation and propagation law and the optimization method of improving the fatigue resistance of metal welding by optimizing the welding process. In 20 years, Zhao Junxian et al. proposed a new kind of splicing of 4 angle steels and spot welding in the middle part, which eliminated the adverse effect of residual stress on the support performance.

3.2. DIC Current Status of Technical Research

Making full use of these correlated features to improve the measurement accuracy and search speed will further improve and develop the image correlation measurement method. In the 80s of the last century, Japan scholar Yamaguchi and Peters et al. proposed a digital image correlation method at the same time. Yamaguchi is using 2D-DIC to measure rigid body motion on a planar object, using such algorithms to determine the amount of translational motion in

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the plane in a laser speckle interferometry environment. Peters used a computer image scanner to record speckle maps before and after deformation, and digitally correlated a subset of the deformed images with the reference value to obtain the displacement vector of the object's surface. In 1989, Gao Jianxin proposed a generalized digital image method, that is, the correlation analysis method, which can directly measure the deformation of objects. In 2002, Hou Zhende et al. proposed a new method for measuring the displacement of image fractal correlation, and compared the test results of the fractal correlation method with the experimental method, the results showed that the fractal correlation method was superior to the reference method. In 2003, Xia Guisuo proposed an improvement scheme for related algorithms, which improved the accuracy and calculation speed of related algorithms. Analyzing the off-site error factors and proposing some solutions can reduce the error in the test process. It provides a new method for DIC technology to be used for deformation measurement and mechanical property study. In 2010, Zhang Rui et al. used DIC technology to measure the elastic modulus of steel strands, and compared with the test results of mechanical extensometers, they basically agreed, and concluded that digital image correlation measurement technology can be used to measure the elastic modulus of steel strands in engineering. In 2012, Qin et al. measured the shear modulus of 3D orthogonal braided C/C composites using digital image correlation techniques, tested both in-plane and penetrating thickness specimens, and obtained macroscopic average strains. In 2013, Pan Bing et al. compared different imaging lenses by comparing two digital images on the surface of the same object before and after deformation, and the results showed that Schneider's bitelecentric lens had little distortion and was insensitive to the effect of the measured object. In 2015, Wang Xiang et al. compared the compression deformation of DIC and strain gauge method to monitor the test specimen, and the test results showed that the strain time curve measured by the DIC system was basically consistent with the curve measured by the strain gauge method.

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