Experimental Mechanics
https://doi.org/10.1007/s11340-024-01068-8

BRIEF TECHNICAL NOTE

Fatigue Testing Approach Utilising Machining Cutting Forces and Fixture Design

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Received: 26 September 2023 / Accepted: 29 March 2024

Abstract

Background Traditional fatigue testing methods can be expensive due to the need of specialised equipment for engineering materials and structures. Thus, a new fatigue testing approach utilising machining cutting forces to induce cyclic stresses, enabling fatigue life assessment of engineering materials and structures, has been developed.

Objective This research aims to develop and verify a new testing approach using machining processes to enable the fatigue life assessment of engineering materials and structures. This is achieved by the utilisation of machining-induced cutting forces to generate cyclic stresses into welded samples used in applications of wind turbine monopile structures.

Methods The methodology employs the development of a fixture encompassed with strain gauges and purposefully designed machining operations to mimic the cyclic stresses experienced in real applications. The machining-based fatigue testing approach was demonstrated on welded samples by replicating cyclic stresses of offshore wind turbine monopiles subject to in-service loads.

Results The results show that rapid fatigue testing of engineering materials and structures is possible by utilising existing machine tools and centres, which are widely accessible to industry. Cyclic stresses were induced in welded structural steel samples proving the concept of this method.

Conclusion This novel fatigue testing method showed that cyclic stresses can be induced by machining cutting forces to address real application needs. The key advantages are that this method can be quickly set up in industry, enabling fast fatigue testing that can lead to reduction of lead times for product and process development of industrial components.

Keywords Fatigue testing method · Cyclic stresses · Machining · Cutting force

Introduction

Fatigue is a pervasive issue that affects many industries, including aerospace, automotive, nuclear healthcare, and others [1, 2]. Structures, particularly those bearing loads, frequently fail due to fatigue [3, 4]. To enhance the service life of components, fatigue needs to be tackled throughout the whole lifecycle. In industry, metal components are often exposed to repeated, or 'cyclic', loading. To prevent fatigue failures, these components must be designed in conjunction with an accurate assessment of fatigue. In many engineering applications, components experience cyclic loads along multiple axes due to complex loadings as well as specific notches and geometries [5]. Furthermore, a fatigue assessment may require the relationship between stress and number of cycles (S-N curve) through uniaxial or rotating-bending loading, development of fatigue load cases, calculation of the stress field, and prediction of the number of cycles using fatigue theories. The S-N curves obtained from fatigue testing vary widely due to factors like surface morphology, manufacturing defects, and anisotropic behaviour [6]. The S-N curves can be obtained using traditional fatigue testing systems, but they can be expensive and time-consuming [7]. For instance, it takes about 46 h for a servo-hydraulic test machine running at 60 Hz to complete 10^7 rounds for a point on a S–N curve in a uniaxial fatigue test and more factors have been identified

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as high cost and limited availability for biaxial testing, complexity of resonant testing procedures as they require special controlling devices, difficulty in obtaining fatigue limit strengths data for materials subjected to more complex loading, and limitation to uniaxial tension including ultrasonic machines operating at 20 kHz [8–11]. Although ultrasonic fatigue testing systems can address some of these issues, they have limitations such as specimen size and shape limits, test monitoring, equipment complexity, and costs [12–15].

In contrast to the existing methods and practices for fatigue testing, this research introduces a novel fatigue testing method for the first time which uses machining to generate cyclic stresses as seen in service to enable fatigue life assessment of engineering materials and structures. As an exemplar, the testing process is demonstrated on welded samples by mimicking in-service cyclic stress conditions of wind turbine monopile structures. The versatility of this fatigue testing method lays in the design of a fixture that can enable the test of artifacts with different geometries and loading conditions. In addition, machining processes and cutting parameters can be set to induce multi-directional cyclic stresses simultaneously, which can be a challenge with traditional fatigue testing methods.

Conceptual Design

In fatigue testing, the development of specialised jigs to mimic in-service load requires a significant effort and utilisation of resources. The design, fabrication and commissioning of a test rig would require substantial lead time too. Therefore, a new concept is proposed for fatigue testing by the utilisation of machining processes. The principle of the concept is that the induced cutting forces from machining processes (e.g., milling), which have a cyclic nature, are used as a loading condition to induce a stress field in the component, which in this case is a welded structural steel specimen. Figure 1 shows the concept of a clamped welded S355G10 + M structural steel sample, which is attached to a specifically designed and fabricated fixture. A block of unmachined sacrificial material is attached to the top of the fixture. The block is then machined, where cutting forces are induced and transferred into the welded specimen through a bending moment. Depending on the type of the cutting tool (end mill, ball end mill, drill, grinding wheel), cutting parameters (depth of cut, feed rate, spindle speed), type of cutting operation (up milling, down milling, drilling, grinding), the cutting forces can be induced in the three directions of the Cartesian coordinate systems. The variety of available cutting tools and machining operations provides the flexibility to design the cutting forces in a way that in-service induced cyclic stresses can be mimicked. The cutting forces are determined based on depth of cut, uncut chip thickness, cutting speed, cutting tool geometry, surface conditions, temperature and material properties [16, 17]. However, this needs to be combined with the dimensions of the unmachined block of material as well as the designed fixture that will be capable of controlling the distribution of the induced cutting forces by using purposely designed supports in the fixture [18]. Through the induced cutting forces, the tested component can experience loading along different axes including the combination of bending, tension, compression, and torsion.

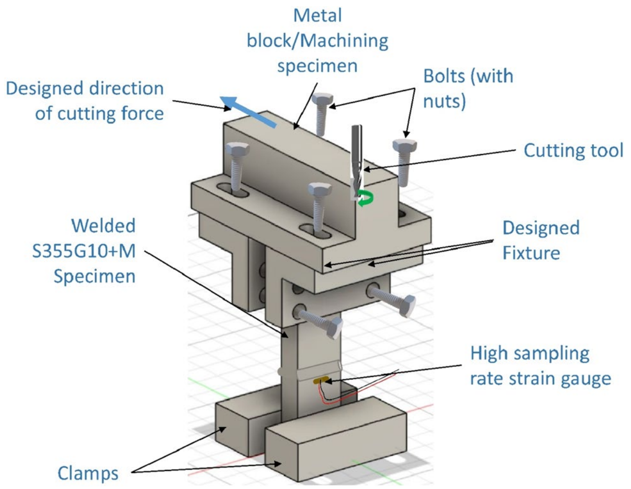

Fig. 1 Illustration of the concept

Verification of Fatigue Testing Using Milling

The fatigue testing using a milling machine tool was set up as illustrated in Fig. 2. A strain gauge capable of recording a high sample rate was connected to the InstruNET [19] data acquisition system. For each test, a sample rate of 1666.7 samples/secs and a two-flute cutting tool with a diameter of 10 mm were used. The surfaces of the S355G10 + M steels were marked out at the weld zone region, cleaned with solvent cleaner, and sanded using silicon carbide sheets of grades 60, 120, 240, 320, 400, 600, and 800 to ensure surface smoothness and prevent stress altering in the material. Afterwards, a conditioner was applied and sanded. The precise position where the centre of the strain gauge backing would rest was carefully marked on the sides. A cotton swab dipped in neutraliser was applied in the area prepared for bonding. A tape was applied to the back of the InstruNET-R-120 (120 Ω resistance) strain gauge. A strong temperature-resistant adhesive was applied to the marked area, and the strain gauge was carefully placed in such a way that the tip of the strain gauge backing was on the weld toe as well as in the direction of the expected stress distribution.

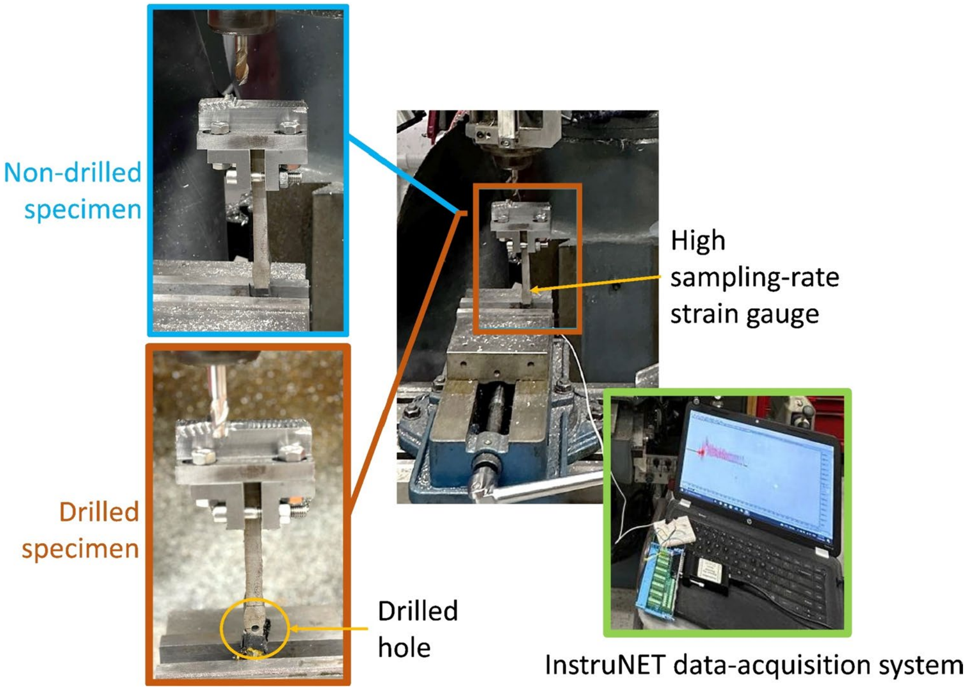

Fig. 2 Fatigue testing using milling machine tool and designed fixture

The weld toe is a critical area in welded structures where stress concentrations are high, making it a valuable location for measuring strain due to induced cyclic stresses, especially in fatigue testing. A radial depth of cut of 5 mm, axial depth of cut of 4 mm, a feed rate of 0.075 mm/tooth and a spindle speed of 500 rpm were applied. The selected milling parameters were selected to induce cyclic stresses in the axial direction at the weld toe, which is the location where fatigue crack could be induced in offshore monopile structures [20]. This innovative approach involves the indirect application of load for fatigue testing, contrasting with the conventional methods that typically apply load or displacement directly.

The welded samples were manufactured by submerge arc welding of S355G10 + M structural steel used for offshore and marine applications. The welding process utilised a solid wire electrode EN ISO 14,171-A: S3Si (IABCO 2.4/3.2 mm), and the flux was EN ISO 14,174: SA FB 155 AC H5. The mechanical properties of the welded S355G10 + M included a yield stress of 501 MPa, an ultimate tensile strength of 590 MPa and 29% elongation. Double V-groove and multi-pass technique were applied for optimal weld quality. After welding, dye penetration inspection was conducted to check the weld beads for its surface quality according to BS EN ISO 23,277 [21]. After welding of plates with 10 mm thickness, waterjet cutting was employed to cut samples usingan 87,000 Psi Dynamic Waterjet XD machine. The cold-cutting prevented material damage, and it eliminated the creation of heat affected zone, stress buildup, and structural alterations. The obtained sample dimensions were according to ASTM E466 [22] with a gauge length of 82 mm and a cross section of 12.5 mm × 10 mm as shown in Fig. 2. An initial trial showed that stresses of approximately 50 MPa were measured at the weld toe where the strain gauge was attached. However, the process induced self-excited vibrations (chatter), which limited the increase of the cutting forces. To induce higher stresses in the welded sample, a 5 mm hole was drilled in the 10 mm thick welded sample to increase the stress level at the weld toe while keeping the cutting forces the same. Drilling a hole reduced the cross-sectional area at the weld toe and increased the stress due to bending while maintaining a stable milling.

Results obtained from the machining are shown in Figs. 3 and 4 for drilled and non-drilled specimens in a stress-time curve where the material was under cyclic tension. The maximum measured stress values are 211 MPa and 59 MPa for drilled and non-drilled specimens, respectively. The test with drilled specimen shows that the minimum stress is close to zero for some cycles and the overall maximum stress is approximately 200 MPa. The higher stresses for the drilled specimen are due to the generated bending stresses from the reduced cross-sectional area. Figures 3 and 4 show that the mean stress is not a constant value. The non-constant mean stress is due to the cutting tool exerting forces on the specimen's surface affected by cutting depth, speed, and the cutting tool creating bending moments that change depending on the tool's location. Since the induced bending moments vary with the cutting tool's position, the stress distribution across the specimen also changes during the testing. This results in a mean stress that is not constant but fluctuates

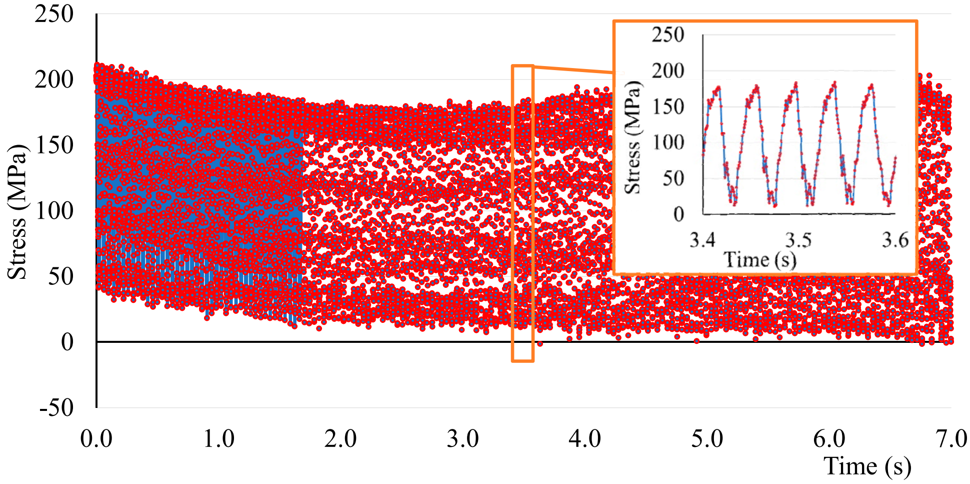

Fig. 3 Stress-time curve for drilled specimen utilising milling to simulate in-service load

as the machining process progresses. Different areas of the specimen might experience tension or compression at different times, leading to a dynamic stress environment [23].This can reflect a scenario where structural components undergo complex stress cycles, not just uniform loading [24]. The change of the cutting direction can also change the induced stress (tension or compression). The combination of these options can be integrated into a computer aided manufacturing (CAM) strategy to generate a toolpath capable of simulating in-service cyclic stresses. The induced stresses can be modified by varying the depth of cut and the feed rate to achieve different levels of cyclic stresses, and replicating different wind loads. For faster testing, the spindle speed can be increased to reach a higher number of cycles for less milling time. However, the increase of the spindle speed might change the dynamics of the machining operation leading to undesirable vibration. Therefore, stable (chatter free) conditions need to be determined to achieve higher material removal rates [25], hence inducing higher cutting forces and cyclic stresses.

In wind turbine monopile structures, the induced bending stresses are caused by wind and wave loads [26]. The average stress ratio was calculated based on the measured cyclic stresses. It was obtained that the average stress ratio for drilled specimen and non-drilled specimen is 0.11 and -0.08 respectively. The positive R-ratio indicates that the drilled specimen has experienced a loading cycle with tensile mean stresses. This is more common in fatigue testing, and it can be representative of the actual service conditions of wind turbine monopiles, where fluctuating tensile stresses due to wind and waves are expected. It is used to adjust fatigue life calculations based on the influence of mean stresses, and it is in line with typical design scenarios according to the recommendations of fatigue design code DNVGL-RP-C203 [27].

To compare the method with a traditional uniaxial tensile testing method for wind turbine welded structures, four fatigue tests were performed on the same non-drilled welded 10 mm thick dog-bone S355G10+M specimens using a 250 kN Instron servo-hydraulic testing machine at frequency of 10 Hz and a stress ratio of $R=0.5$. Considering results

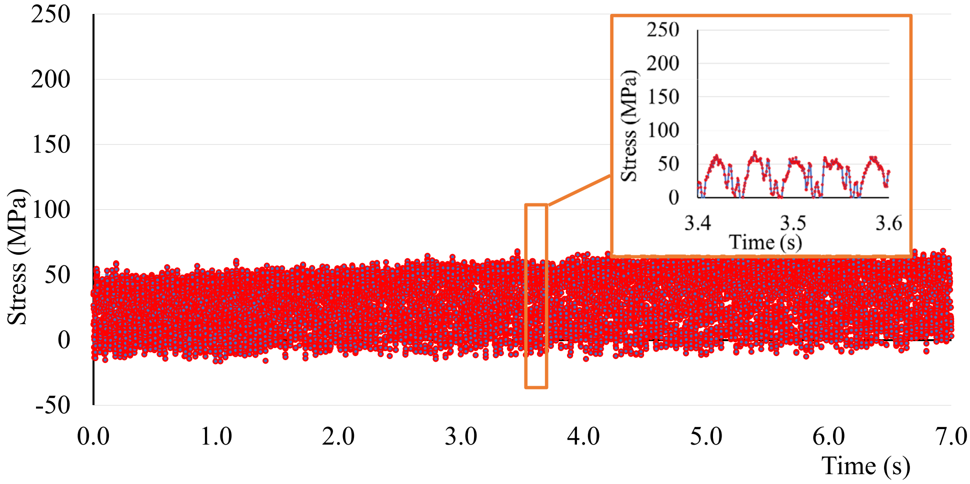

Fig. 4 Stress-time curve for non-drilled specimen by utilising milling to simulate in-service load

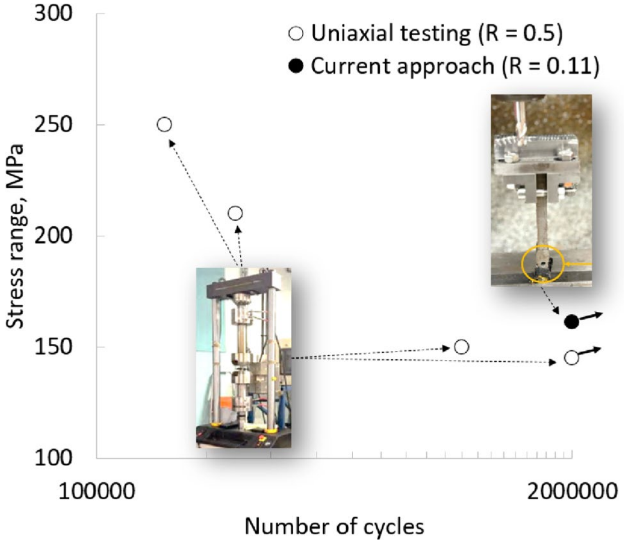

Fig. 5 Stress range versus number of cycles for welded S355G10+M samples obtained with two fatigue testing methods

from fatigue testing at $R = 0.5$, the number of cycles at 150 MPa stress range is approximately 1,000,000 cycles with a run-out of 145 MPa at 2,000,000 cycles (see Fig. 5). The two conducted tests (non-drilled and drilled samples) using the novel method showed no cracks after 2,000,000 cycles. The average stress range for the drilled sample was obtained to be 161 MPa while the fluctuation of the stress range was in the range of 150–200 MPa. For comparison to the uniaxial testing at $R = 0.5$, a data point with a run-out is added for the proposed new method with a stress range of 161 MPa at 2,000,000 cycles at $R = 0.11$. It is expected that at a lower stress ratio, the stress range should be higher. For instance, for similar welded samples, Okenyi et al. [28] reported the stress range at $R = 0.1$ was approximately 20% higher than at $R = 0.5$.

Conclusions

This novel fatigue testing method showed that cyclic stresses can be induced by machining cutting forces to address real application needs. The key advantage is that this method can be quickly set up in industry, enabling fast fatigue testing that can lead to reduction of lead times for product and process development of industrial components. A limitation of the testing method is the lack of full control of the cutting forces due to their dependence on the cutting tool condition, process parameters, induced vibrations and material properties of the cutting material.

As a future perspective, the measured stresses over time can be used to conduct fatigue analyses using rainflow counting and damage calculations. Furthermore, the proposed method has a great transformative potential to be further explored by designing smart fixtures for more complex components and applying multiaxial loading conditions using toolpath design with computer-aided manufacturing tools. The repeatability of this approach is another area that requires further research.

Data Availability All data supporting this study's findings are included in this study.

Declarations

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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