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Research Article

Experimental Research on Dynamic Behavior of Circular Mild Steel Plates with Surface Cracks Subjected to Repeated Impacts in Low Temperature

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Experimental investigations on the mechanical responses of fully clamped circular plates with prefabricated crack at room temperature and low temperature have been conducted. Initial cracks with different lengths were prefabricated by the electrical discharge machining method. Low ambient temperature was created by the liquid nitrogen in a low-temperature chamber, and a dropping hammer was dropped from the same height with a constant impact energy of 5 J to carry out the repeated impact. Experimental test results show that the prefabricated crack has a significant influence on the mechanical behavior of the thin plates. The maximum impact force decreases with increase of the crack length, and the threshold impact number until fracture decreases with increase of the crack length. It is also observed from the test results that the maximum impact force increases with decrease of the temperature, while threshold impact number until fracture and the plastic permanent deformation decreases due to the brittleness of the material in low temperature. The present investigations provide useful insight into the failure mechanism of the clamped thin plate with initial crack under low-velocity repeated impacts in low temperature, which will lead to a guideline for research and design of marine structures in the arctic area.

1. Introduction

In recent years, affected by global warming, exploration of the arctic trading route is becoming a new research hotspot. When the polar ships travel in arctic areas, the ship structures may suffer from severe conditions: firstly, low temperature may affect the mechanical properties of the structure material; on the other hand, floating objects such as flow ices may repeatedly impact the structure with minor energy and may cause permanent plastic deformation. Such factors may significantly reduce the load carrying capability of the structures and even cause catastrophic damage. Besides, potential minor crack may occur during fabrication and operation or could be caused by corrosion during the life cycle service, and there is a growing interest in understanding the influence of the initial crack on the load carrying capability of the structures [1]. Therefore, it is of importance to evaluate the dynamic behavior of structure with surface cracks under the combined load of repeated impacts and low temperature.

Ships and marine structures often suffer from various forms of repeated impacts during their life cycle, such as violent slamming or green water and continuous ice floe striking. Thus, research on dynamic responses of the marine structure under repeated impacts could date back to the 1970s [2]. Jones [2] conducted an analytical method for predicting plastic deformation of a rectangular plate under slamming impulse and later a theoretical research on the dynamic behavior of plate under multiple mass impacts [3]. Zhu and Faulkner [4] proposed experimental and theoretical investigations on the behavior of rectangular plate under repeated impacts of a wedge indenter and presented a simplified theoretical formula to estimate plating damages. Huang et al. [5] proposed explanation of pseudoshakedown of ship plates under repeated mass impacts based on the energy criterion both experimentally and theoretically and indicated that the elastic strain energy absorption increases with that of the plastic deformation of the structure for the axially restrained ship plate subjected to repeated dynamic loads. Cho et al. [6] and Truong et al. [7] conducted experimental and numerical research on the steel slender beam subjected to repeated impacts and proposed that the incremental permanent plastic displacement decreased with the impact number increasing. Recently, repeated impacts of composite materials and structures are of new research interest. Atas and Dogan [8] proposed experimental investigation on the repeated impact response of glass/epoxy composites and indicated that impact resistance of glass/epoxy composites decreases with increasing impact number due to material degradation. Akatay et al. [9] and Balcı et al. [10] conducted experimental results of dynamic responses of repaired sandwich panel which are composed of fiberglass composite face sheets and aluminum sandwich core under repeated impacts. Truong et al. [11] proposed experimental research on steel grillage under repeated impacts. Guo et al. [12] proposed experimental and numerical investigations on aluminum foam core sandwich structure under repeated impacts and indicated that plastic deformation energy decreased with the impact number.

Uniaxial tensile test results [13, 14] show that mechanical properties such as yield stress, strain hardening effect, necking instability, and fracture strain are strongly affected by the ambient temperature environment; hence mechanical responses of ship structure in low ambient temperature are also affected. Ehlers and Østby [15] studied the collision resistance of ships exposed to ultralow temperature. Noh et al. [14] and Min et al. [16] proposed experimental research on impact of girders with notches at room temperature and low temperature. Kim et al. [17] found that steel stiffened panel undergoes a premature brittle fracture due to brittleness of the steel at an ambient temperature of −60°C, and numerical simulation research had been established. Besides, impact resistance of composite structures such as laminar composites [18] and aluminum foam sandwich panels [19] at low temperature had been investigated, and similar brittleness and strain hardening effect phenomena had been discovered.

In the past decades, researchers focused on the residual ultimate strength and load carrying capability of a cracked structure. Paik et al. [20] proposed a general expression of the ultimate strength of a plate with longitudinal crack based on experimental investigation and numerical simulation and later discussed the influence of the crack direction on the load carrying capability of the cracked plate [21, 22], in which the plate with a crack parallel to the load direction has a better load carrying capability rather than that with a crack perpendicular to the load direction is shown. Dündar and Ayhan [23] proposed the in-plane residual strength, fracture, and fatigue crack propagation of a stiffened plate with multiple cracks. Theoretical, experimental, and numerical research on the ultimate strength of cracked structures is also presented in References [24–27]. However, research on load carrying capability and crack propagation of a crack plate under repeated impacts is limited.

To date, little investigations have been made into the dynamic behavior of cracked plate under repeated impacts in low temperature. This paper aims to investigate sensitivity of the clamped circular plates to initial cracks in low temperature, and experimental research on dynamic behavior of circular mild steel plates with surface cracks subjected to repeated impacts at room temperature and low temperature was conducted by using the drop hammer tower test machine. Room temperature of 20°C and low temperature of −40°C were selected as the ambient temperature. Time history of the impacting force curves was obtained, impact number till rupture was tested, and the permanent deflections of the plates were measured. The influences of the temperature and crack length on the impacting force, impact number till rupture, and the permanent deflection of the clamped circular mild steel plates are compared and analyzed.

2. Specimen Design

2.1. Material Properties Test. The room temperature is between 10°C and 38°C, and it is chosen to be 20°C in the present paper. Meanwhile, the target low temperature was chosen based on the average winter temperature in the arctic area (−40°C) [28]. Mild steel was utilized in the present research, and the mechanical properties were tested at room temperature and low temperature firstly. According to the regulations in GB/T 228.1 [29] and GB/T 13239 [30] for unidirectional tensile tests at room temperature and low temperature, respectively, the tensile test coupon was designed, as shown in Figure 1.

The test coupons were taken from a 2 mm thickness plate. As shown in Figure 2, mechanical properties of the steel were tested with the universal tensile test machine. The test coupon was fixed to the tensile test machine by two-pin connections. The connections, the coupon, and the extensometer were located in a low-temperature chamber. Liquid nitrogen was used to create a low ambient temperature environment. After the coupon had been fixed to the connections, liquid nitrogen was pumped into the low-temperature chamber to cool the temperature in the chamber. The tensile test would be executed until maintaining the designated temperature for at least 60 min.

Figure 3 shows the relationships between engineering stress versus strain which were obtained from the tensile test at different ambient temperatures. It is observed from Figure 3 and Table 1 that the yield stress and ultimate strength of the mild steel tend to increase as the temperature decreased, while fracture strain is observed to decrease as the temperature decreased.

2.2. Specimen Fabrication. The specimen for repeated impact experiment is a square with a side length of 100 mm and a thickness of 2 mm. Geometric parameters of the specimen are shown in Figure 4, and 12 holes with a diameter of 12 mm are circumferentially distributed on the plate, through which the plate would be bolted to the support. In order to avoid the residual stress during fabrication, a wire cutting method had been adopted in the fabrication. The initial crack is located in the center of the square plate, with a

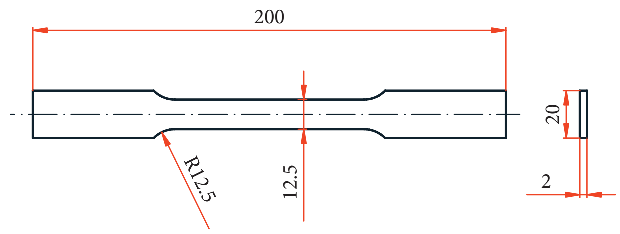


Figure 1: Geometric configurations of the tensile test specimen (unit: mm).

Figure 2: Universal tensile test machine.

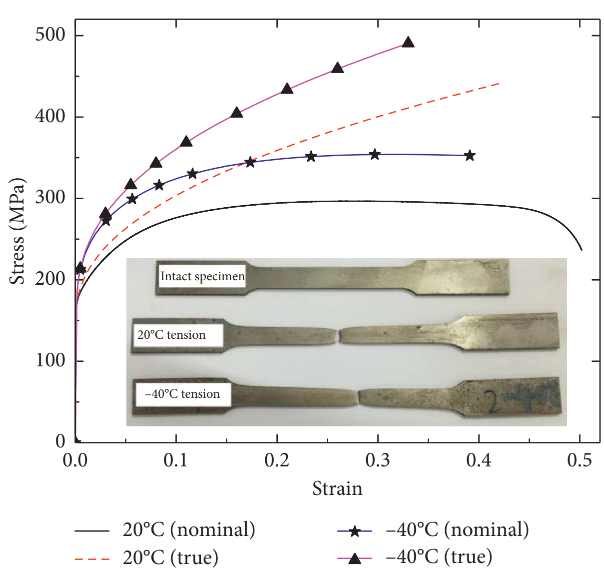


Figure 3: Stress-strain curves of the mild steel at different temperatures.

depth of 1 mm and a length of L. Three values of the crack length are obtained, $L = 5$ mm, 15 mm, and 25 mm, respectively.

Table 1: Tensile test results at different temperatures.

Property	Unit	Ambient temperature	
		20°C	−40°C
Density	$kg\cdot m^{-3}$	7850	7850
Poisson's ratio	—	0.3	0.3
Elastic module	GPa	202	212
Yield stress	MPa	168	184
Fracture strength	MPa	441	490
Fracture strain	—	0.42	0.33

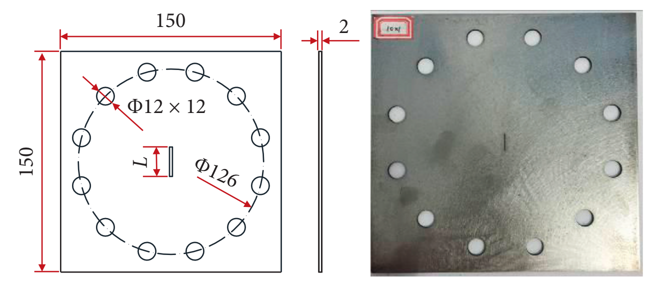


Figure 4: The cracked square specimen (unit: mm).

The cracks were prefabricated by an EDM (electrical discharge machining) system, as shown in Figure 5. EDM is a feasible solution for machining surface cracks in the present investigation, which have varied lengths and depths with a strict precision requirement. As shown in Figure 6, the electrode fed vertically downwards by 1 mm, which determines the crack depth; then the horizontal feeding was given, and the feed distance was determined by the crack length. The electrode moves at constant speeds in vertical and horizontal directions with 0.03 mm accuracy. The specimen and the electrode were immersed in the working fluid during the prefabrication process, and the circulating working fluid can wash away the electrolytic products and cool the specimen.

3. Experimental Setup

3.1. Drop Hammer Impact Tower. The repeated impact investigations of the cracked plates were carried out by a drop hammer impact tower, as shown in Figure 7. The indenter with a mass property of 13.28 kg, which consists of three parts, the impact mass, the force transducer, and the impactor, is guided by two vertical rails. The impactor which is a hemisphere ended steel cylinder with a diameter of 15 mm can be assumed to be a rigid body due to the surface hardening fabrication technique. During an impact process, the initial impact energy is achieved by adjusting the drop height of the indenter. The hammer was released from the same height, which would ensure that the specimen suffered repeated impacts at a same energy and at the same location. Furthermore, a pneumatic driven rebounding catcher was installed to prevent the rebound hammer from unexpected twice impact in one hammer dropping process.

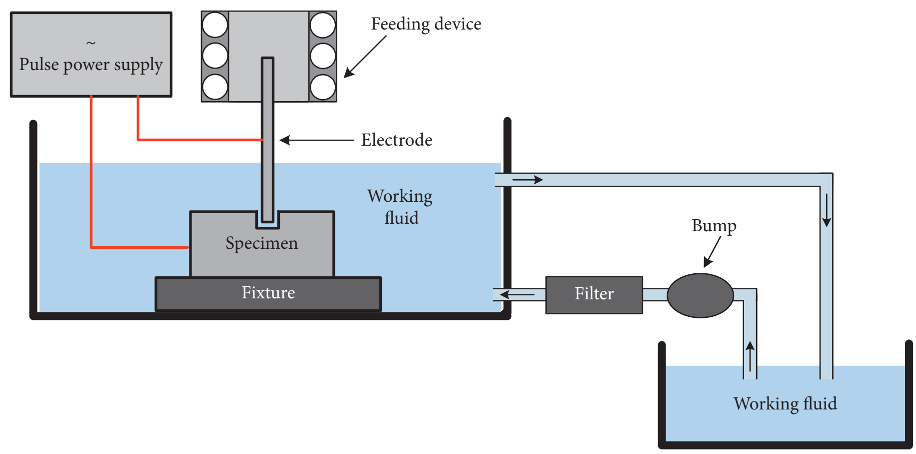


Figure 5: Diagram of crack prefabrication.

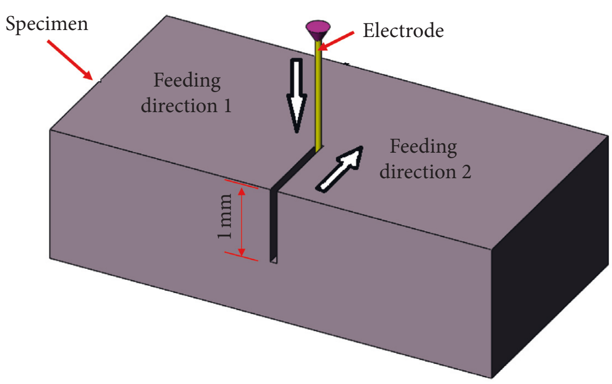


Figure 6: Detailed machining process of prefabrication of the crack.

As shown in Figure 8, the specimens were placed between the clamp and the rigid base, with the prefabricated crack on the lower surface and fixed together by the 12 circumferentially distributed bolts. Both the clamp above the specimen and the rigid base below the specimen have a circular hole of 75 mm. This arrangement would provide a fully clamped boundary condition, of which means that no rotation, axial movement, or lateral movement occurs at the circular edge. The clamp, the specimen, and the rigid base are located in the low-temperature chamber. After the specimens were fixed perfectly, liquid nitrogen was pumped into the low-temperature chamber by using a pneumatic pump to obtain the designated ambient temperature in the chamber. The low-temperature chamber had an automatic control system which consists of several electromagnetic valves, fans, and temperature transducers. The quantity of supercooled nitrogen pumped into the chamber could be adjusted automatically to maintain the expected test condition with a temperature control accuracy of ±2°C. The impact test would be executed until maintaining the designated temperature for at least 60 min.

3.2. Measurements. As shown in Figure 7, a piezoelectric force transducer is connected to the impactor to measure the contact force during impact process with a sampling frequency of 1.25 MHz, and the force-time relationship could be established directly by the data acquisition/processing program.

After each hammer drop impact, the permanent deformation of the specimen was measured by the laser displacement measuring equipment, as shown in Figure 9. The deformed specimen moved vertically with a velocity of 5 mm/min driven by the moving platform, and then the permanent deformation along the lines that crossed at the center of the specimen (as shown in Figure 9) was measured by the laser displacement sensor.

4. Results and Discussion

4.1. Impact at Room Temperature. Compared with the intact specimen, the load carrying capacity of the cracked specimen is greatly reduced under impact load [1]. The cracked specimen undergoes a premature fracture under high energy impact, which may cause difficulty in exploring the regulation of failure propagation. In contrast, if the impact energy is relatively low, the cracked specimen may undergo a slower crack propagation and a late maturing fracture and would cause a larger time and financial consumption. Hence, it is of importance to select the appropriate impact energy. Through a series of trial and error, an impact energy of 5 J was selected to carry out a series of impact tests finally.

Three specimens with different crack lengths had been tested under repeated impacts at 5 J of energy each time until fracture. The crack length expressed as a symbol L are converted to a dimensionless factor L/D by taking its ratio to the diameter of the impactor D. Subsequently, the symbol L/D equals to 1/3, 1, and 5/3 for the three specimens with different crack lengths, respectively.

Figure 10 shows the time history of impact forces. For all the impact scenarios, the impact force-time curves increased and decreased smoothly. As the impacts are repeated, the maximum contact force increased significantly, while the impact duration decreased. This phenomenon is mainly due to the strain hardening effect. The residual plasticity increased incrementally with the increase of the impact number, accordingly the maximum force increased.

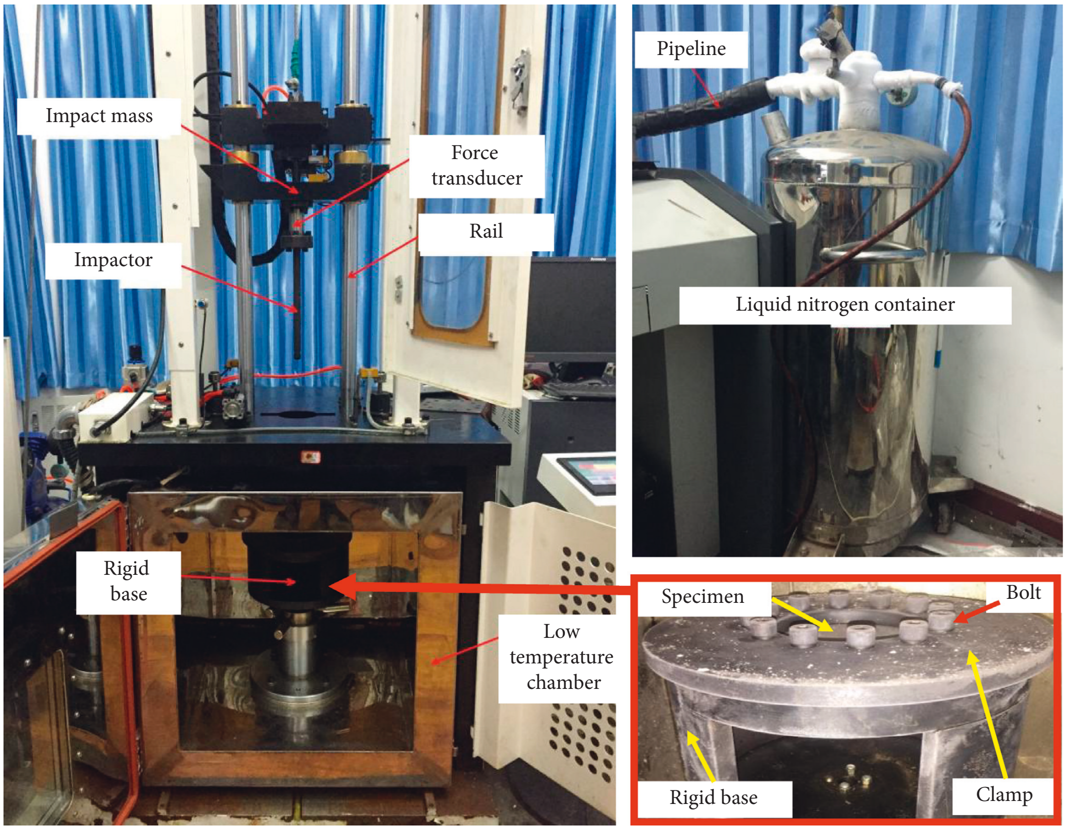


FIGURE 7: The drop hammer impact test machine.

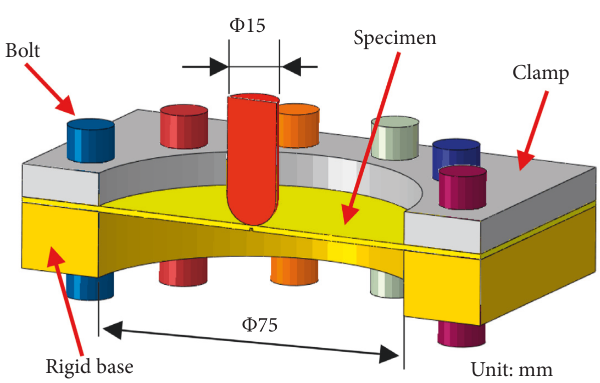


FIGURE 8: Schematic diagram of the clamped method.

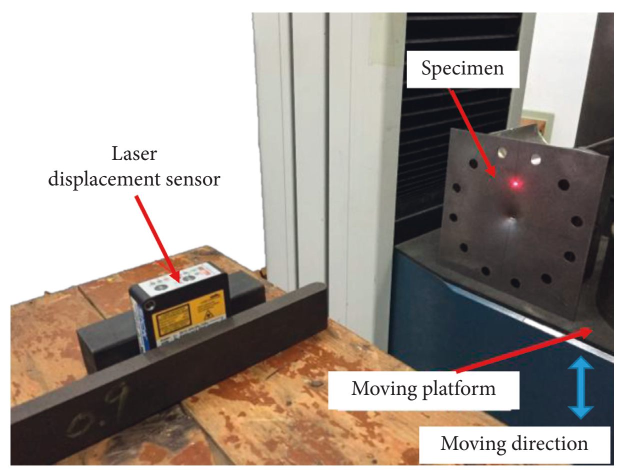


FIGURE 9: Deformation measurement setup.

In the first impact, all the three cracked specimens are trended to similar responses, and the maximum impact force curves are relatively close to each other. In particular, the two curves of specimens with the L/D ratio of 1 and 5/3 are substantially coincident. In the third impact, the impact force of all crack length plates is also relatively close, and the impact force peak is about 3.5 kN. The impact responses definitely show that the crack length has little effect on the mechanical responses during the beginning stage of the repeated impacts. With the increasing impact number, the effect of the crack length on the impact responses of the plate under repeated impacts became more significant than that in the lower repeated number impacts.

The specimen with the longest prefabricated crack ($L/D = 5/3$) was perforated in the 9th impact, the specimen with the L/D ratio of 1 was perforated in the 14th impact, while the specimen with the shortest prefabricated crack ($L/D = 1/3$) was perforated in the 21th impact. This phenomenon indicate that the crack length will affect the load carrying capacity of the plate and the specimen with the longest crack undergoes the lowest residual load carrying capability and the lowest energy absorption capability under repeated impacts and may suffer a premature fracture.

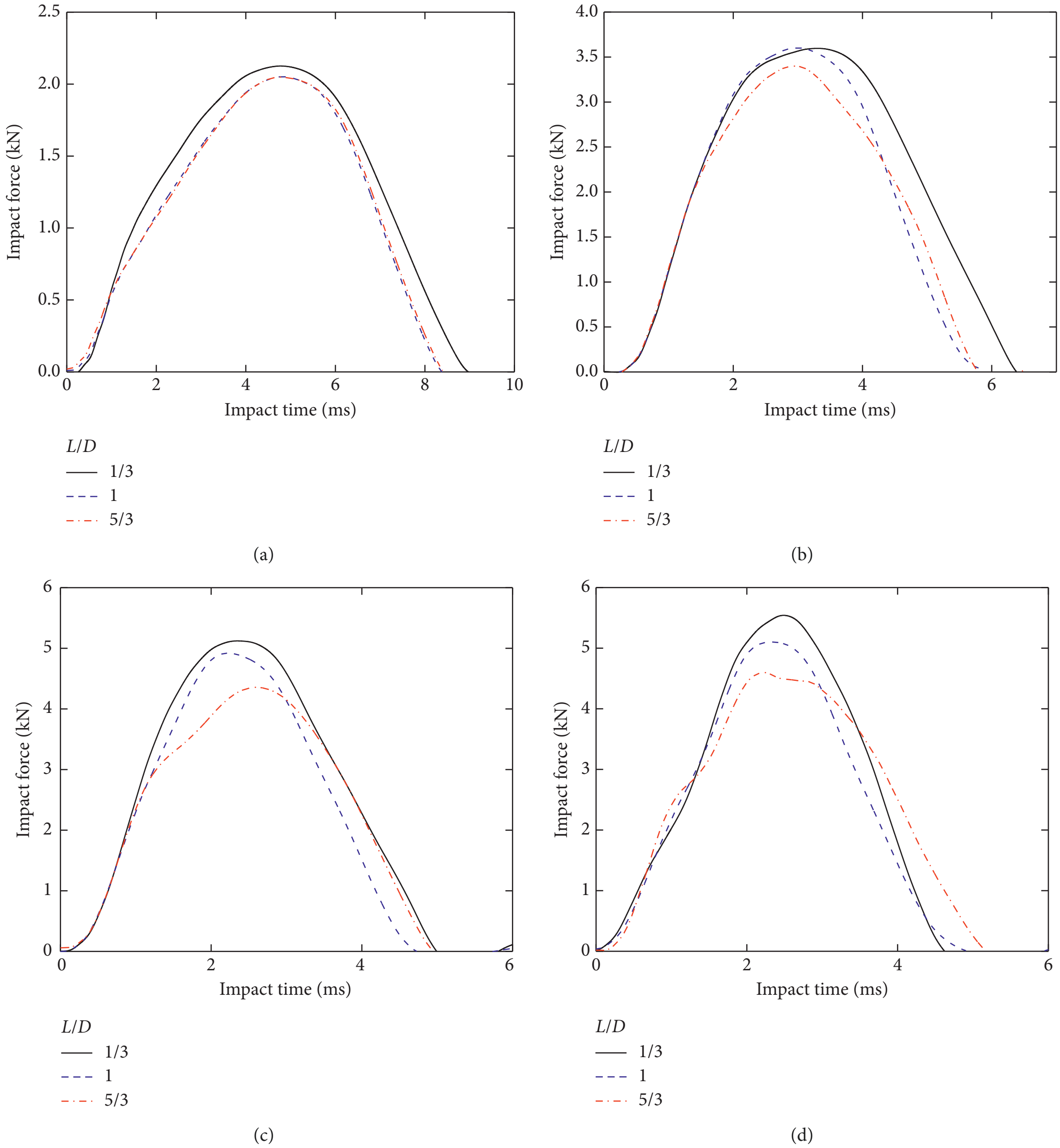


Figure 10: Continued.

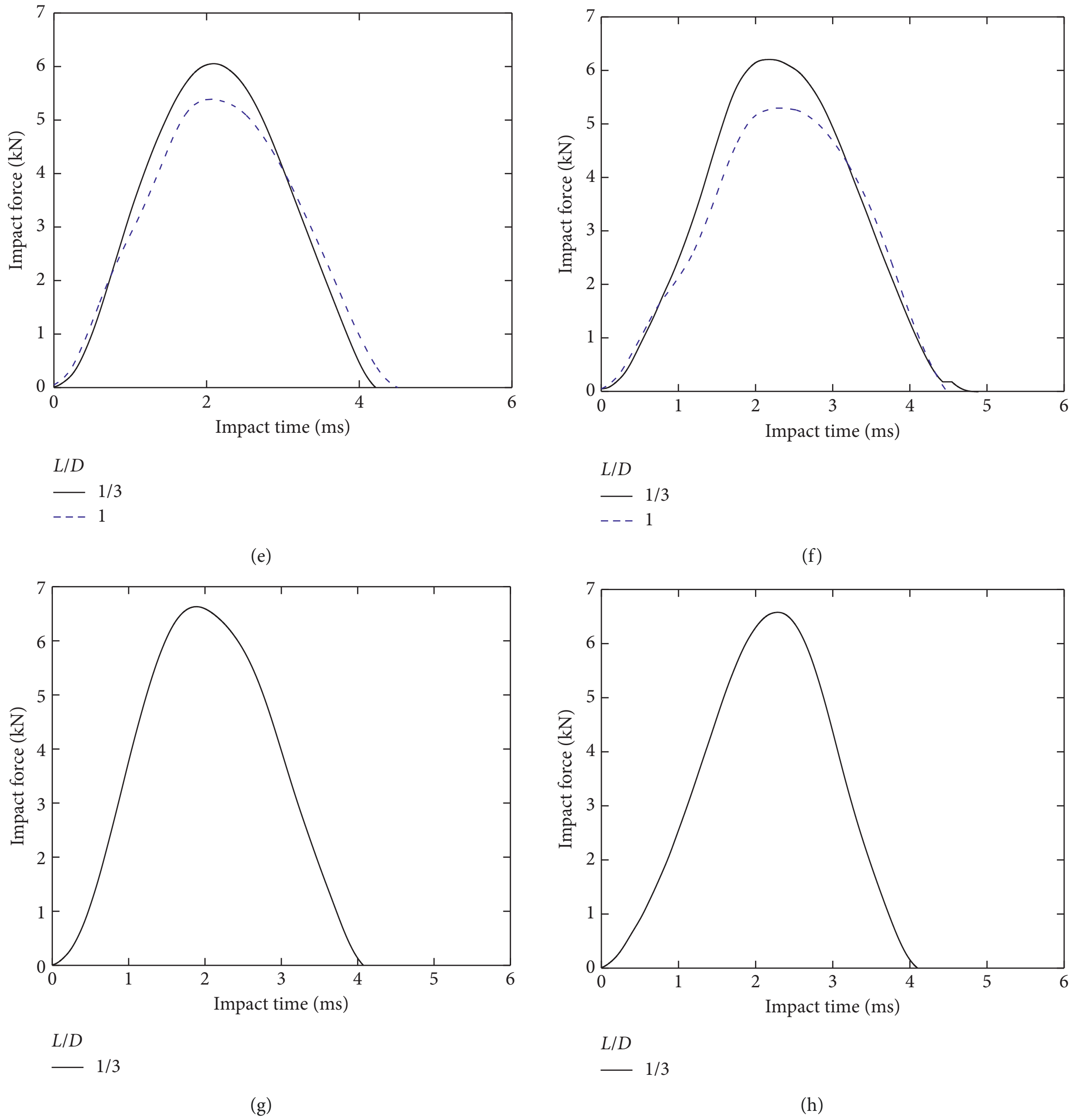


Figure 10: Time history of impact force at room temperature. (a) 1st impact. (b) 3rd impact. (c) 6th impact. (d) 9th impact. (e) 12th impact. (f) 14th impact. (g) 18th impact. (h) 21st impact.

Damage evolution of the specimens is listed in Figure 11, which definitely shows that an initial crack affects the damage mode significantly. Specimens with different L/D ratios would yield quite different modes in crack initiation and propagation. The damage modes can be divided into two types:

(1) For specimen with a short initial crack ($L/D = 1/3$), new cracks appear at both ends of the initial crack in the perpendicular direction due to the stress concentration at the very end of the initial crack. Cracks propagated forward around the dent marks as the impact number increased until the perforation of the specimens, and the specimen undergoes an I-shaped crack at the rear surface.

(2) For the specimen with longer initial crack ($L/D = 1$, 5/3), the initial crack propagated along its length direction from the center and then extended sideways. The plates were penetrated at the center of the crack finally as the impact number reached the threshold value.

4.2. Impact at Low Temperature. Similarly, three specimens with an L/D ratio of 1/3, 1, and 5/3 had been tested under repeated impacts at 5 J of energy each time until fracture at −40°C ambient temperature.

Threshold impact numbers until fracture both at room temperature and low temperature are shown in Figure 12. Compared to the impact at room temperature, the

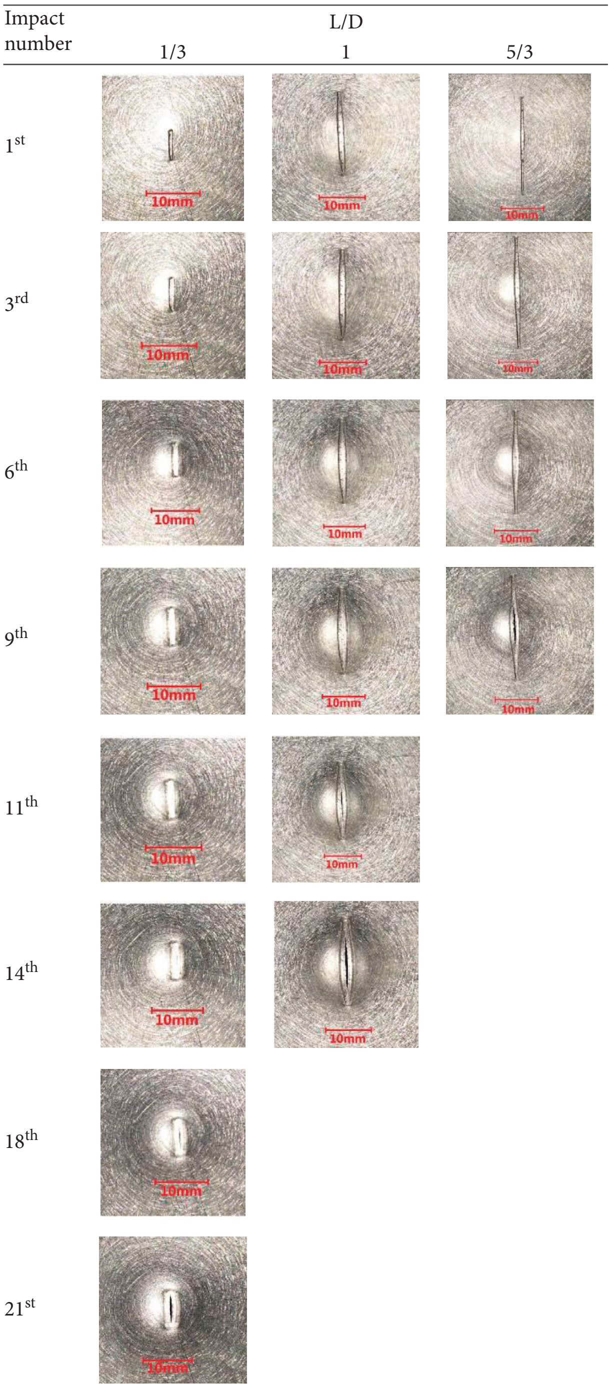


Figure 11: Deformation mode under repeated impacts at room temperature.

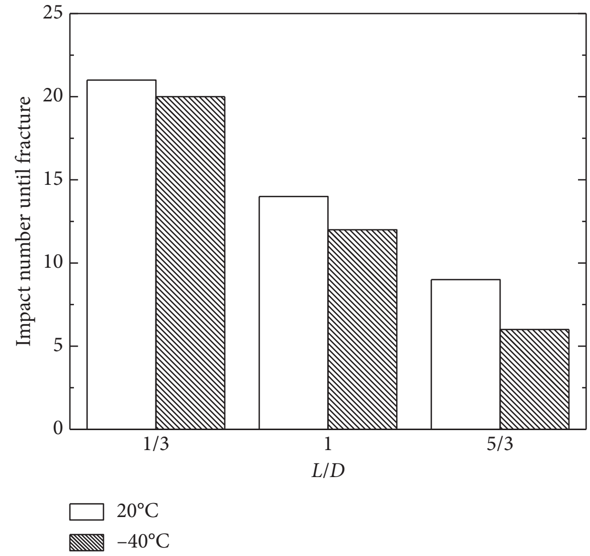


Figure 12: Threshold value of impact numbers until fracture.

specimens were perforated during 20th, 12th, and 6th impact for the specimen with an L/D ratio of 1/3, 1, and 5/3 at low temperature. As shown in Figure 3 and Table 1, fracture strain is observed to decrease as the temperature decreased. Actually, ductility of the material decreases, which may lead to the decrease of the energy absorption capability under impact. Furthermore, the specimen with longer initial crack undergoes a larger shutdown of the threshold value of impact numbers at low temperature rather than at room temperature.

The impact force-time curves of the specimen at low temperature are similar to those at room temperature, and the slopes are relatively similar. In order to reduce the paper length and make the manuscript more concise, only the maximum impact forces for each impact scenario are compared in this section. Figure 13 present the maximum impact forces both at room temperature and low temperature. It is shown in Figure 13 that the maximum impact force increases slightly with the decrease in ambient temperature for specimens with the same crack length in the same impact number, which is mainly due to the material strengthening at low temperature. Due to the increase of fracture stress and decrease of fracture strain at low temperature, maximum impact force slightly increased due to a larger stiffness; furthermore, a premature fracture occurred at low temperature.

It can be observed from Figure 13 that when the impact number is less than 5, the influence of low temperature on the mechanical responses are not obvious, and maximum impact forces are relatively close to each other. With the impact number increased, the influences of low ambient temperature become much more significant. The maximum impact forces at low temperature are 2.5%–4.9% larger than that at room temperature.

The maximum permanent plastic deformations are listed in Table 2 and Figure 14. The plastic deformations increased incrementally with the increase in the impact number. It is shown in Figure 14 that plastic deformation at room temperature is larger than that in low temperature. In addition, the differences become more obvious as the impact number increases. For example, for the specimen with the shortest crack length ($L/D = 1/3$), the permanent plastic deformations at low temperature are close to those values at room temperature when the impact number is less than five; as the impact number increased, the differences between the two values become larger incrementally. Furthermore, the ambient temperature has a more significant influence on the permanent deformation of the plate with a longer

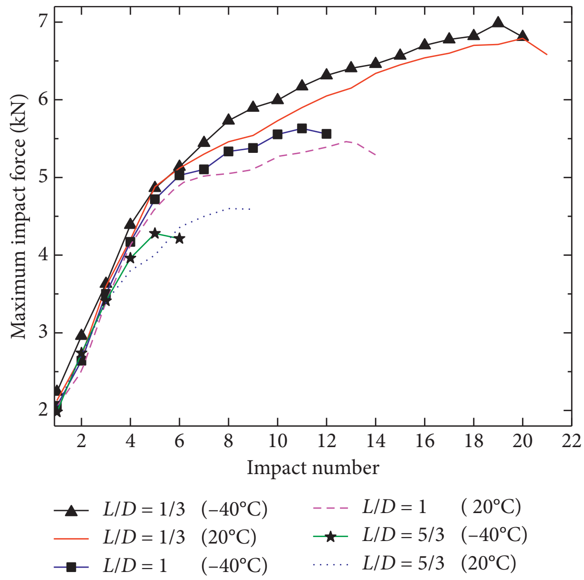
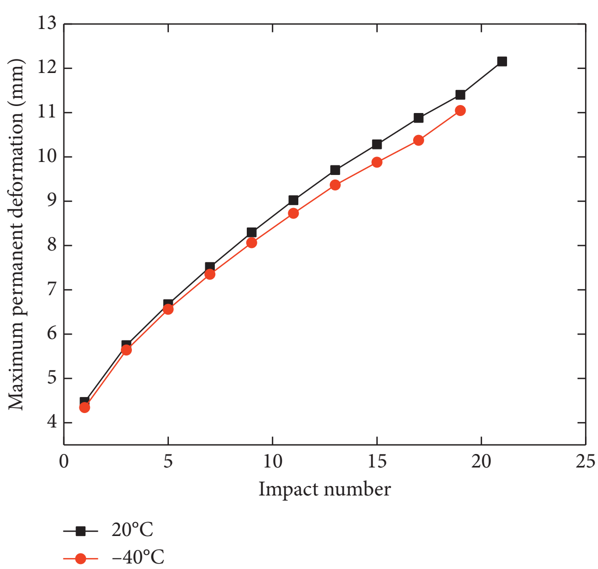


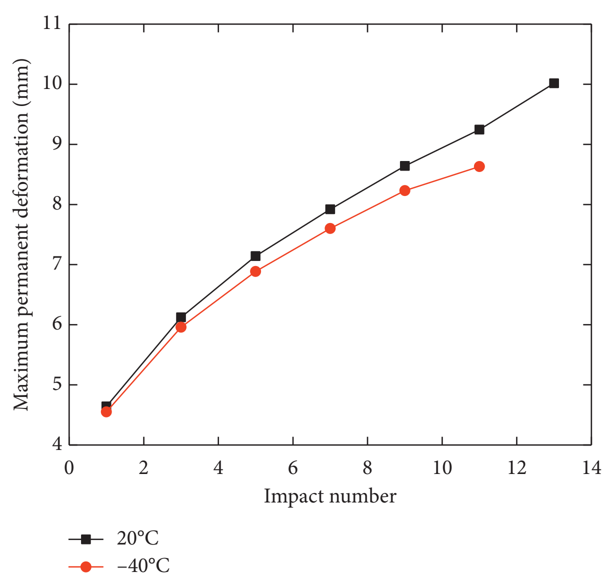
FIGURE 13: Comparison of the maximum impact force at different temperatures.

TABLE 2: Maximum lateral plastic deformation at different temperatures (unit: mm).

Impact number	$L/D = 1/3$		$L/D = 1$		$L/D = 5/3$	
	20°C	−40°C	20°C	−40°C	20°C	−40°C
1	4.467	4.341	4.641	4.550	4.643	4.598
3	5.749	5.639	6.124	5.960	6.099	5.942
5	6.674	6.558	7.141	6.887	7.128	6.865
7	7.513	7.349	7.920	7.600	7.915	—
9	8.296	8.061	8.641	8.231	8.761	—
11	9.020	8.725	9.244	8.631	—	—
13	9.701	9.365	10.015	—	—	—
15	10.283	9.880	—	—	—	—
17	10.880	10.374	—	—	—	—
19	11.400	11.046	—	—	—	—
21	12.154	—	—	—	—	—

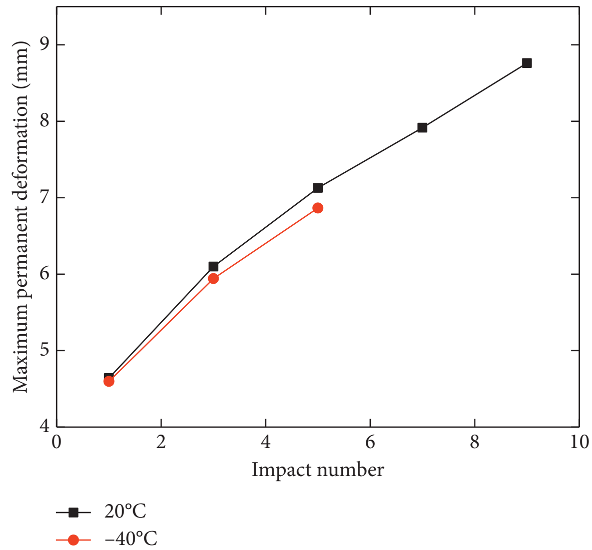


(a)



(b)

FIGURE 14: Continued.



(c)

FIGURE 14: Maximum lateral plastic deformation at different temperatures. (a) $L/D = 1/3$. (b) $L/D = 1$. (c) $L/D = 5/3$.

prefabricated crack. When the specimens with the L/D ratio of 1/3, 1, and 5/3 are perforated, the final permanent plastic deformation at low temperature is 9.12%, 13.82%, and 21.64% less than that at room temperature, respectively.

5. Conclusion

Experimental investigations on the mechanical responses of fully clamped circular plates with prefabricated crack at room temperature and low temperature have been conducted in the present research. Mechanical properties of the material have been tested, and repeated impact experiments have been carried out. The impact responses including impact force, permanent deformation, threshold impact numbers, and failure mode of the cracked plates under repeated impact at different ambient temperatures have been measured and compared. Useful conclusions have been achieved as follows:

(1) Mechanical properties of the mild steel are strongly affected by the ambient temperature. The yield stress and ultimate strength of the mild steel tend to increase as the temperature decreased, while fracture strain is observed to decrease as the temperature decreased. Altogether, the strength of the material increases while the ductility decreases as the temperature decreases.

(2) The prefabricated crack has a significant influence on the mechanical behavior of the thin plates. The peak force decreases with the increase of the crack length when subjected to repeated impacts under the same impact energy; the threshold impact number till the fracture of the plate decreases with the increase of the crack length.

(3) The ambient temperature will strongly affect the mechanical responses of the plate under repeated impacts for specimens with the same initial crack length. The peak impact force increases with decrease of the temperature, while the repeated impact number till fracture and the plastic permanent deformation decreases due to the brittleness of the material at low temperature.

The present investigations provide useful insight into failure mechanism of thin plate with initial crack under low-velocity repeated impacts at low temperature, which would lead to a guideline for research and design of marine structures in the arctic area.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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