Effect of loading protocol on the mechanical properties of 316L stainless steel

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Abstract. Two types of loading protocol, i.e., monotonic loading and cyclic loading, were compared to investigate the effect on the mechanical properties of 316L stainless steel. The specimen used is a dog-bone specimen in accordance with ASTM E8 and ASTM E606 standard. For cyclic loading, the multiple-step method is used to obtain the hysteresis loop of the material. A total of 13 strain amplitude conditions had been carried out, ranging from 0.05%-0.65%. The stress-strain curve shows that the cyclic stress-strain curve is higher than the monotonic stress-strain curve due to the cyclic hardening behaviour in the 316L stainless steel. The cyclic hardening behaviour increases the ultimate tensile stress of the material. However, when the material gains its strength through cyclic hardening, the ductility in the material will decrease.

1. Introduction
The 316L stainless steel is prevalent stainless steel in construction and marine project due to its high temperature and high corrosion durability. The everyday use of 316L stainless steel, including the construction of heats exchanger, exhaust manifolds, furnace part, evaporators, and tanks to withstand high-pressure condition. The mechanical behaviour under cyclic loading depends on the material; the response of the material can show strain hardening, strain softening, stable behaviour [1]. Many researchers had investigated the effect of cyclic loading on the metal material, such as the Bauschinger effect [2] and cyclic strain hardening and softening [3] on the metallic material.

G. Yu et al. [4] investigate the effect of different pre-strain and strain amplitudes on 304 stainless steel and ST12 cold-rolled plates under cyclic tension-compression loading. Both materials show cyclic softening as the plastic energy decrease during the loading. C.D. Annan and E. Beaumont [5] found that material behaviour showed cyclic hardening if the cyclic stress-strain curve is over the uniaxial stress-strain curve. Monotonic loading and cyclic loading test were carried on finding the mechanical properties of AISI 1022 HR and G4.21 350WT steels. The tensile strength and yield strength increase while the ductility decreases as the elongation percentage decreases throughout the
cyclic loading test [6]. Strain hardening will improve the strength of metal from the dislocation movement within the material's crystal structure during the plastic deformation process [7].

The cyclic stress-strain curve is beneficial for finite element analysis as the ductile material's crack growth gives more accurate results when compared with experiment results [8-9]. The area under the stress-strain curve is indicating the energy density of the material. High energy density means that the material can absorb significant energy before it fractures [10]. There are three methods to carry out cyclic loading: the multiple steps, the incremental step, and the companion method. R. Halama [11] used the incremental step method to find the effect of the uniaxial test and biaxial test on ST 52 steel. A total of five strain amplitude in individual loading block was used in the cyclic loading. Each block consists of 25 cycles. The strain control experiment showed strain hardening in the material. An extremely low cycle fatigue test was carried out by companion method to study the mechanical properties of structural carbon steel and stainless steel; the stainless steel is found to exhibit a more significant cyclic hardening [12]. Y. Wang and Z. Wang found that strain hardening characteristics exist in cyclic loading by companion method compared to monotonic loading [13].

This paper mainly finds the mechanical properties of 316L stainless steel by two types of loading, i.e., monotonic loading and cyclic loading, to investigate the effects on the mechanical properties of the materials. The experiment testing included one monotonic loading test and 13 cyclic loading tests. The cyclic loading test was carried out by the multiple-step method in a single specimen approach. The monotonic behaviour and hysteresis behaviour of the material were analyzed.

2. Methodology

2.1. Specimen Preparation

A material used was 316L stainless steel, and a dog-bone shaped specimen was used for both monotonic and cyclic loading tests conditions. Figure 1 shows the dimension of the specimen in accordance with ASTM E8 [14] and ASTM E606 [15], respectively. The dog-bone specimens for monotonic and cyclic loading tests were prepared by laser cutting to eliminate the residual stress in the specimens. The specimen had gauge length, which is the smaller width at the middle part of the specimen. The gauge length is an area where fracture usually occurs when the specimen expends equally during the elongation. The dimension of the monotonic dog-bone specimen is more extended than the cyclic dog-bone specimen.

![Figure 1. Dog bone specimen in accordance with ASTM standard (in mm).](image)
2.2. Experimental Setup

Figure 2(a) and (b) show an experimental setup for the monotonic and cyclic loading test, respectively. Tensile tests were carried out under monotonic loading condition to obtain the mechanical properties by using Universal Testing Machine (UTM). The specimen will be loaded for monotonic loading until the specimen reaches its maximum tensile and fails. The specimen will go through three stages which is elongation, necking, and fracture. The material properties such as young modulus, yield stress, ultimate tensile stress can be extracted from the stress-strain curve obtained.

On the other hand, fatigue tests were carried out under cyclic loading conditions using Nano Plug and Play Servo-hydraulic testing machine to identify the materials’ cyclic behaviour. An extensometer was mounted at the gauge length of the dog-bone specimen to collect the strain data throughout the test. The frequency used was 0.005Hz as low frequency will provide more data to obtain peak shape in the hysteresis loop. Strain control was used in the test, and the extensometer was used to monitor strain during the test.

The multiple-step method was used to collect the cyclic data. The strain amplitude used was set from the range of 0.05% to 0.65%. was used in the test. One test was conducted for each condition in different amplitude with a total of 13 strain amplitude conditions. For each strain amplitude condition, the test was stops when it reached a cyclic stable state condition, then the test continued with an increment in the strain amplitude value. The cyclic loading stress-strain curve can be plotted by connecting the peak stress values of each cycle in the hysteresis loop obtained from the cyclic loading experiment [12].

(a) Monotonic loading  
(b) Cyclic loading

Figure 2. Experimental setup.

3. Results and Discussions

3.1. Monotonic Loading

The material properties for 316L stainless steel were obtained from the stress-strain curve under monotonic loading condition plotted in Figure 3. The yield stress was estimated by using 0.2% offset method, which is defined as the amount of stress in the material with plastic strain of 0.2%. According to the stress-strain curve, the yield strength is 205MPa while the ultimate tensile stress is the highest value of stress throughout the monotonic loading, which is 545MPa. Besides that, the modulus of elasticity is 193GPa, calculated by linear elastic line below the yield stress point.
3.2. Cyclic Loading
The cyclic dog-bone specimen was cyclically loaded through the test to study the hysteresis behaviour of the material. Figure 4 shows the typical stress-strain hysteresis loop of cyclic loading with a strain amplitude of 0.35% in a stable state condition. The test was performed within the range of strain amplitude, $\Delta\varepsilon$ until a stable state condition loop was obtained. From the loading-unloading process between minimum to maximum stress, the hysteresis loop was formed.

A total of 13 cyclic loading tests condition with strain amplitude ranging from 0.05%-0.065% were carried out. All the hysteresis loops obtained from each strain amplitude condition test were plotted into a graph as shown in Figure 5. The materials’ cyclic behaviour can be identified by a fitting curve which can be plotted by connecting the peak stress of each hysteresis loop. The point of the fitting is indicating the minimum stress and maximum stress of each cycle.
3.3. Comparison between Monotonic and Cyclic Loading Conditions

Figure 6 shows a comparison between monotonic and cyclic loading curve. By comparing the monotonic and cyclic stress-strain curve, the cyclic stress-strain curve moves higher than the monotonic loading due to the cyclic hardening behaviour. The energy density of the material, which is the area under the stress-strain curve of the cyclic loading, is higher than monotonic loading. Therefore, when a material undergoes a cyclic loading, it can absorb more energy before it fractures.

4. Conclusions

The monotonic and cyclic tests were successfully carried out on the material 316L stainless steel. Throughout the study, the main conclusions can be obtained from all the above research,

(a) The cyclic stress-strain curve is vital in the numerical simulation to estimate a structure's fracture toughness in seismic conditions such as cyclic J-integral. The result will be more accurate when compared with the experiment test because it is closer to real-life situations.

(b) The yield stress, ultimate tensile stress, and modulus of elasticity found from the stress-strain curve are 205MPa, 545MPa and 193GPa, respectively.

(c) When comparing the curve from two types of loading protocol, the 316L stainless steel exhibited a cyclic strain hardening behaviour. The yield stress of the cyclic stress-strain curve is higher than the monotonic stress-strain curve, while the modulus of elasticity of both curves is close. The cyclic loading stress-strain curve moves higher than the monotonic loading.
stress-strain curve after the yield stress. The cyclic hardening behaviour increases the ultimate tensile stress of the material. However, when the material gains its strength through cyclic hardening, the ductility in the material will decrease.

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