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Tensile Strength Study of Stainless-Steel using Weibull Distribution

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ABSTRACT

In the present study, the distribution pattern of the ultimate tensile strength of 304-grade stainless steel was investigated using a two-parameter Weibull distribution function. During tensile testing, it was observed that the ultimate tensile strength varied from specimen to specimen (ranges from 878 to 1006 MPa). The results have revealed that the distribution pattern of the tensile strength can be described by the two-parameter Weibull distribution equation. Moreover, the fracture statistics of the stainless steel were examined by plotting the survival probability of the specimen against the applied stress to the specimen. It has been observed that the relationship between the survival probability and the applied stresses can be described by the Weibull model. It also provides design engineers with a tool that will help them to present the necessary mechanical properties with confidence.

1. INTRODUCTION

Bangladesh enjoyed GDP growth of 8.1% in 2019 and is set to continue at a fast pace in the near future (United Nations, 2020). The dramatic rise in GDP has resulted in the rapid development of infrastructures and the construction industry has seen stellar growth with a rate of 16.25% (Islam *et al.*, 2016). It has been reported that Bangladesh will need to construct approximately 4 million new houses annually over the next twenty years to meet the future demand for housing (Bony & Rahman, 2014). It is noteworthy that most of the construction practice in Bangladesh is concentrated on reinforced concrete (RCC), which affects the environment directly such as global warming, the depletion of natural resources, waste generation and pollution etc. According to the Department of Environment (DoE) and the World Bank, traditional brick-making industries account for 56% of air pollution in Dhaka city (Islam, 2015). Hence to reduce air pollution, the Bangladesh government has decided to phase out conventional bricks by 2025 from all construction works (Rahman, 2019). From this point of view, sustainability construction concepts get more importance nowadays, where stainless steel is used as a building material due to durable, recyclable, and reusable characteristics (Aksel & Eren, 2015). In this context, the demand for steel in load-bearing structural applications has been gradually increasing in Bangladesh, mainly owing to their favourable properties such as high strength, better strength to weight ratio, attractive appearance, high fire and corrosion resistance, ability to retain its strength even at high temperatures, fabricability, weldability and so on (Monrrabal *et al.*, 2019; Wang *et al.*, 2019; Monteiro *et al.*, 2017; Feng *et al.*, 2019; Khatak *et al.*, 1996). In recent times, the steel is found to use for a range of structural applications in Bangladesh including:

1. Cladding and roofing applications in the transport sector for a load-bearing member, for example for bus frames (Chakma, 2019).
2. Prefabricated steel structures for different purposes such as setting up factories, multi-storied buildings, power plants and bridges, readymade garment factories, textile mills, pharmaceuticals industry (Nur, 2016).
3. Concrete filled stainless steel tube (CFSST) where a rectangular or circular cross-section steel tube is filled with concrete used in various constructions (Sanaullah *et al.*, 2019).

Therefore, mechanical properties such as strength is very important for the structural and architectural application of steel. Generally, conventional macro tensile tests are commonly used to evaluate mechanical properties such as yield strength, ultimate tensile strength, and ductility. To allow for effective comparison on macroscopic tensile test results, specific details (such as (i) shapes and sizes of the specimen, (ii) straining rates, (iii) methods of measurements, and (iv) data analysis, etc.) of the standard tensile test have been formulated. ASTM-E8/E8M (ASTM E8/E8M-16ae1, 2013) provides full descriptions of testing methods. Based on the macroscopic viewpoint, the mechanical properties of metallic materials are considered homogeneous. However, in the real material, a considerable amount of scattering is observed. The scatter in mechanical properties results from various uncertainties of different origins: (i) the variations in physical or chemical features during manufacturing processes (Azeez *et al.*, 2019), (ii) microstructure stochasticity due to thermo-mechanical processing (such as rolling and extrusion) and heat treatments (Birbilis *et al.*, 2006; Király *et al.*, 2018), (iii) machining and preparation method of the specimen resulting in the variation of residual stresses (SungHo *et al.*, 2010), (iv) variation of bulk defects (Azeez *et al.*, 2019). As a result, the mechanical properties vary from specimen to specimen, even though nominally identical specimens were tested under the same loading conditions (such as loading mode, speed). This indicates that the tensile testing data are not deterministic rather statistical. Hence, the inherent scatter behaviour of tensile properties needs to be assessed probabilistically.

In recent years, the Weibull distribution function has been extensively used for assessing the mechanical properties (both static and dynamic) of metallic materials (Hallinan *et al.*, 1993; Bedi *et al.*, 2009). One of the main reasons is that the probability density function of the Weibull distribution has a wide variety of shapes. For example, when the shape parameter is equal to 1, it becomes the two-parameter exponential function, whereas when the shape parameter is equal to 3, the function can approximate a normal distribution. Thus, the Weibull distribution has been proven to be useful to describe the statistical behaviour of tensile strength of many materials, such as ceramic (Glaeser *et al.*, 1997), metal matrix composites (Fukui *et al.*, 1997), fatigue properties of metallic materials (Evans *et al.*, 1983; Mohd *et al.*, 2015; Wang *et al.*, 2001; Bhuiyan *et al.* 2016). In the context of engineering design and reliability of structures, a good understanding of the scattering behaviour of the ultimate tensile strength of stainless steel may shed light on their safe utilization in design and manufacturing. Therefore, in the present study, the variation of the tensile strength of 304 stainless steel has been analysed using the Weibull distribution function. Finally, the reliability of the material in terms of ultimate tensile strength was presented in graphical form.

2. Experimental Procedure

A. *Material and Specimen Preparation*

The material used in the present study was a 304 Grade stainless steel plate (with composition (mas%) 0.0243~0.0268C, 0.334~0.352Si, 7.86~7.90Ni, 1.41~1.42Mn, 0.0242~0.0252P, 0.0056-0.0057S, 18.23~18.25Cr, 0.154~0.152Mo, 0.0804~0.0821Co, 0.144~0.145Cu, 0.0035~0.0036Ti, 0.0973~0.0976V) from STEELTECH company and was kindly supplied by the Civil Engineering Department of the Military Institute of Science and Technology (MIST).

From the supplied rectangular 304 stainless steel pipe, tensile test specimens with dimensions 136 mm (total length, L), 6 mm (gauge width, W), and 2 mm (thickness, T) were machined using a CNC milling machine, following the ASTM-E8 standard (ASTM E8/E8M-16ae1, 2013). The specimen geometry is shown in Figure 1.

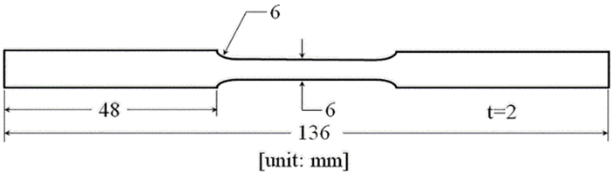

Figure 1: Geometries of mechanical test specimens

B. *Tensile Testing Procedure*

In total 10 specimens were prepared for tensile testing. Prior to tensile testing, the width and thickness of each specimen were measured at three locations in the gauge section, and an average cross-section area is calculated. Each specimen was then broken in a universal tensile testing machine with a crosshead speed of 1 mm/min.

For metallographic examination, samples were polished with 280 to 1500 grit emery papers in laboratory air. In the final polishing step, a 3-micron diamond paste was used. The freshly polished specimen was then etched using a solution containing 20 mL nitric acid and 60 mL hydrochloric acid following ASTM 407-07 (ASTM standard 407-07, 2005). The specimens were then observed under an optical microscope.

C. *Theoretical Background*

Based on the weakest-link hypothesis, Weibull proposed a simple distribution function for strength, σ. Its two-parameter form takes the form (Weibull, 1951):

$$F(\sigma_i;\sigma_0,m)=1-exp\left[\left(-\frac{\sigma_i}{\sigma_0}\right)^m\right]\sigma_0>0,m>0 \qquad (1)$$

where $F(\sigma_i;\sigma_0,m)$ is the probability of failure, σ_0 is the characteristic tensile strength (alternatively referred to as scale parameter) where 63.2% of samples fail (36.8% survival probability for samples stressed at loading equal to σ_0), σ_i is the variable (ultimate tensile strength in the present study), and m is the slope of the curve known as shape parameter (alternatively referred to as Weibull modulus) and is a measure of data scattering and the scale parameter σ_0.

The Weibull modulus, m, is estimated using one of the three methods: (i) linear regression, (ii) maximum likelihood, and (iii) moments. However, the commonly used method is linear regression because of its simplicity and relative ease in use (Tiryakioğlu, Hudak, & Ökten, 2009).

By taking the natural logarithm of both sides of Equation (1) twice yields:

$$ln\left[ln\left(\frac{1}{1-F(\sigma_i;\sigma_o,m)}\right)\right] = mln(\sigma_i) - mln(\sigma_o) = mx + c \quad (2)$$

In Weibull statistics, the following four probability estimators are commonly used (Bergman, 1984; Datsiou *et al.*, 2018):

$$F(\sigma_i;\sigma_0,m) = \frac{i}{n+1} \quad (3a)$$

$$F(\sigma_i;\sigma_0,m) = \frac{i-0.5}{n} \quad (3b)$$

$$F(\sigma_i;\sigma_0,m) = \frac{i-0.3}{n+0.4} \quad (3c)$$

$$F(\sigma_i;\sigma_0,m) = \frac{i-0.375}{n+0.25} \quad (3d)$$

where i is the index of the ascending, n is the sample size (10 in the present study).

Bergman (1984) reported that probability estimators given by Equation (3d) should be used for a small sample size ($n < 20$). Therefore, in the present study, probability estimators defined by Equation (3d) is used to assign a probability of failure to each ultimate tensile strength data point.

The Weibull modulus, m, and the characteristic tensile strength, σ_0 , can be obtained by plotting $ln\left[ln\left(\frac{1}{1-F(\sigma_i;\sigma_o,m)}\right)\right]$ against $ln(\sigma_i)$. After taking a linear regression of the data point, the slope of the regressed line is the Weibull modulus, m, and the intercept is $mln(\sigma_o)$.

By fitting a straight line or applying the least square method to $ln\left[ln\left(\frac{1}{1-F(\sigma_i;\sigma_o,m)}\right)\right]$ as a function of $ln(\sigma_i)$, the Weibull modulus m is the slope and the scaling parameter or characteristic tensile strength can be determined from the intercept.

3. RESULTS AND DISCUSSION

A. *General Mechanical Properties*

Figure 2 shows the optical microstructure for the material used in this study. A typical step structure is observed. C. A. Della-Rovere *et al.* (2013) and A Bahrami *et. al.* (2019) also reported similar microstructures of 304-grade stainless steel. As reported earlier that in total ten tensile tests were performed and corresponding ten stress-strain curves were recorded for each material. A typical stress-strain curve is shown in Figure 3. It is found that the tensile strength ranges from 878 MPa to 1006 MPa, inferring that the ultimate tensile strength appears to vary from specimen to specimen. Table 1 and Table 2 lists the basic statistical properties of ultimate tensile strength and yield strength of the material used in this study. Note that the coefficient of variation (COV = Standard Deviation (σ)/Mean (μ)×100) is about 4.3% for ultimate tensile strength, and 7.6% for yield strength. Kweon *et al.* (2020) reported that the ultimate tensile strength of 304 stainless steel is in the range of 579 to 750 MPa. But our investigated material showed about 1.75-1.90 times higher value of ultimate tensile strength that was reported by Kweon *et al.* (2020). The observed difference might have resulted due to random experimental errors such as variation in width and thickness in the gauge section, machining of specimen resulting in the variation of residual stresses, microstructural heterogeneity in the gauge section. Since the specimens were prepared using a CNC milling machine, hence all the specimens used in this study were identical in shape and size. Therefore, it is reasonable to assume that the variation of width and thickness in the specimen's gauge section does not influence the observed high value of ultimate tensile. It is well established that during machining because of tool-material interactions, the generated surface is affected through roughness, hardness, residual stress distribution and thereby, influence the mechanical properties of the manufactured parts (Kumar *et al.*, 2017; Ben Fredj *et al.*, 2006; Gürbüz *et al.*, 2017; Ma *et al.*, 2018). H. Sutanto (2007) investigated the characteristics of residual stresses during CNC milling machining and observed that very high compressive residual stress (−375 MPa) was induced at the surface of the work material. H. H. Zeng *et al.* (2017) investigated the residual stresses in micro-end milling considering sequential cuts effect and found compressive residual stresses were induced by milling operations. Therefore, based on the above discussion, it is speculated that compressive residual stresses were also induced during the CNC milling machining. However, the surface residual stress is not measured in the present study. Hence, it can be inferred that both microstructural heterogeneity and the milling machining induced high compressive residual stresses resulted in higher ultimate tensile strength (about 1.75-1.90 times) in the studied material. Furthermore, for precise and accurate characterization of tensile properties, it is instructive to use a more advanced technique such as electro-discharge machining (EDM) for specimen preparation.

Table 1
Statistical Properties of the Ultimate Tensile Strength

Mean value (MPa)	Standard deviation (MPa)	Coefficient of variation (CV)
941	40.4	4.3%

Table 2
Statistical Properties of The Yield Strength

Mean value (MPa)	Standard deviation (MPa)	Coefficient of variation (CV)
577	44	7.6%

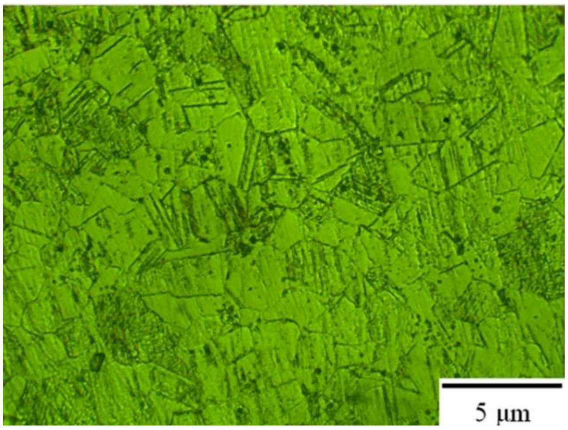

Figure 2: Optical microstructure of 304 stainless steel

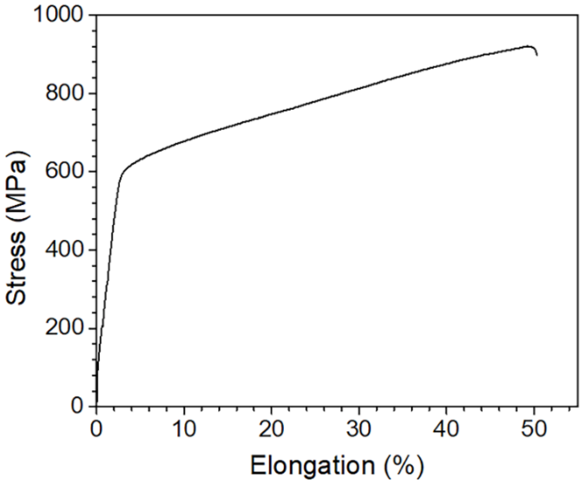

Figure 3: Typical stress-strain curves obtained in the room temperature tensile test

B. Statistical Analysis of Tensile Data

Figure 4 shows the two-parameter Weibull plot of ultimate tensile strength data. The linear regression model with the regression line is also shown in Figure 4. It can be noted that a good linear relationship was observed which suggested that the distribution pattern of the ultimate tensile strength can be reasonably approximated by the Weibull distribution equation.

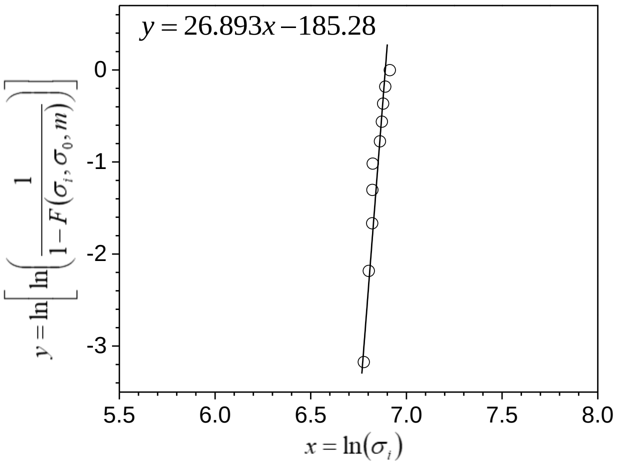

Figure 4: Two-parameter Weibull plot for ultimate tensile strength data

The obtained Weibull distribution parameters such as the Weibull modulus, m, the characteristics tensile strength, σ_o, are listed in Table 2. The slope of the line is 26.893, which is the value of the Weibull modulus. Generally, the shape parameter (or Weibull modulus), $m < 1.0$ indicates that the material has a decreasing failure rate, $m = 0$ indicates a constant failure rate, and $m > 1.0$ indicates an increasing failure rate. Our obtained value m =26.893 clearly indicates that the material tends to fracture with a higher probability for every unit increase in applied tensile load. As mentioned earlier that the parameter σ_0 is the characteristics tensile strength and as a theoretical property $F(\sigma_i; \sigma_0, m) = 0.368$. Based on Table 2, the value of σ_0 is about 982. Therefore, using the value of $\sigma_i = \sigma_o = 982$ and $m = 26.893$, $R(\sigma_i; \sigma_0, m) = R(982; 982{,}26.893 = exp\left[\left(-\frac{\sigma_i}{\sigma_0}\right)^m\right] =$ 0.368, indicating that 36.8% of the tensile tested specimens have a fracture strength of at least 982 MPa.

Table 2
Parameters of two-parameter Weibull distribution

Parameter	Symbol	Values
Shape parameter	m	26.893
Constant term	c	185.28
Scale parameter	$\sigma_0 = e^{\frac{c}{\beta}}$	982

The Weibull reliability distribution curve for tensile strength is shown in Figure 5. It is observed that the tensile strength values of less than 750 MPa are highly reliable. For a more certain assessment, let us consider 0.95 and 0.9 reliability levels. Using these values in Equation (2), the equation is solved for σ_i and the fracture strength values obtained were 879 MPa and 903 MPa, respectively. More specifically, the material will fracture with 0.90 probability for tensile stress of 903 MPa and similarly will fracture with 0.95 probability for tensile stress of 879 MPa.

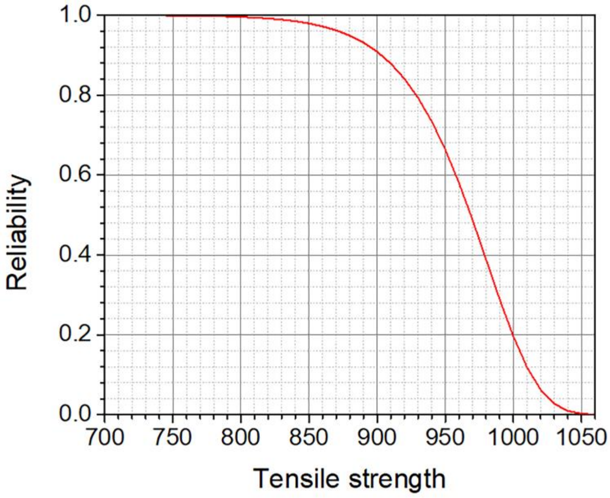

Figure 5: Weibull reliability distribution for tensile strength

4. CONCLUSIONS

In the present study, the distribution pattern of the ultimate tensile strength of 304-grade stainless steel was investigated. The main conclusions obtained are summarized as follows:

1. The ultimate tensile strength of 304 stainless steel appears to vary from specimen to specimen. The tensile strength ranges from 878 MPa to 1006 MPa
2. The distribution pattern of the ultimate tensile strength can be reasonably described by the two-parameter Weibull distribution equation.
3. The characteristic tensile strength, σ_o, obtained is about 982 MPa. Furthermore, the Weibull

modulus (m) for the investigated material is found to be 26.893 inferring that the materials tend to fracture with a higher probability for every unit increase in applied tensile load.

4. The fracture statistics of the stainless steel were examined by plotting the survival probability of the specimen against the stress applied to the specimen. It has been observed that the relationship between the survival probability and the applied stresses can be described by the Weibull model. It also provides design engineers with a tool that will help them to present the necessary mechanical properties with confidence. For example, with a 0.90 reliability level, it was observed that the tensile strength of the present material will be 903 MPa.
5. The varying tensile strengths of stainless steel are due to their inherent internal structures, inferring that there is no specific strength value to represent mechanical behaviour. This study undoubtedly raises questions of assuming the tensile strength as an average of the experimental results. Therefore, the distribution and reliability of mechanical properties especially tensile strength must be described by the probability of function for their safe utilization in design and manufacturing.

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