Evaluation of loading rate to the stress-strain response of reinforcing steel bar

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Abstract. To obtain the material properties of reinforcing steel bar (rebar), a tensile test must be performed in the laboratory. Some standards, such as SNI and ASTM, standardize the condition of the sample and the loading rate of the tensile test. ASTM E8M regulates the loading application (1.15-11.5 MPa/s) of steel rebar test under tension to determine yield properties and SNI 07-2529-1991 governs 10 MPa/s as the maximum loading rate. These circumstances affect the duration of tensile test in real condition, which may lead to one hour of tensile test. In this article, the effect of loading rate of pre-conditioned steel bars (by reducing the section, grinding, and/or lathe according to SNI 07-2529-1991) is investigated using deformed bars (BJTS 40, certified by industries). Random samples of steel reinforcement bar are tested under three different loading rate applications. The result of the material properties of rebar, such as stress-strain curve, yield strength, and ultimate strength, are discussed and analyzed in this study. Different speed tests resulting in different stress rates before yield. However, the stress-strain responses of specimens in the range of linear elastic material are similar. Moreover, at the post-yield/plastic region, the loading rate significantly affected the ductility of the material.

1. Introduction

A tensile test is one of mechanical testing that can be performed to know the material properties of steel reinforcing bars (rebar). Several standards, such as SNI and ASTM, standardize the condition of the sample, the loading rate, and the procedure of the tensile test. Condition of the rebar sample could be reduced, ground, or lathe as regulated on SNI 07-2529-1991 [1]. Whereas, ribs on deformed bars can influence the bond between steel rebar and concrete by increasing their bonding [2]. Then, much attention has been paid to the loading rate of the tensile test to know the most effective speed of the tensile test. However, the loading rate affects the duration of the tensile test in laboratory testing. For example, it may lead to one hour of a tensile test.

In terms of speed or rate of testing, SNI 07-2529-1991 stated that the tensile rate application is uniform and can be adjusted such that the magnitude of the rate of stress does not exceed 10 MPa/s [1]. On the other hand, ASTM E8M regulates some general rules that shall be applied when determining yield and tensile strength. The testing machine shall be operated in a rate of stress in the linear elastic region between 1.15 – 11.5 MPa/s when determining yield properties. For material with more than 5% of expected elongation, the speed of testing machine shall be set in strain rate between 0.05 – 0.5 mm/mm/minute (deformation/minute) when determining tensile strength [3]. Furthermore, the loading rate would affect stress rate, mechanical properties, stress-strain curve, ductility, and modulus of elasticity of steel rebar.
On halves of a broken specimens, steel bars exhibit cup-and-cone fractures [4]. Cup-and-cone fracture looks like a juxtaposition of cups having precipitate or inclusion at their bottom [5]. Cup-and-cone fracture resulted from the former crack of the specimen and shear plane. A former crack of specimen created when a specimen is applied to tensile stress and had a plane perpendicular to applied tensile stress with rough and fibrous fractures surfaces. Shear plane created just before the specimen breaks and formed along the periphery of the specimen with approximately 45° to the tensile test axis [4]. Moreover, the loading rate could affect the mode of failure of the steel rebar. As the loading rate could affect stress rate, mechanical properties, stress-strain curve, ductility, modulus of elasticity, and mode of failure of steel rebar, further discussion is needed to know the effect of the loading rate of tensile test on steel rebar. Therefore, this research would like to analyze and discuss the effect of loading rate of tensile test on steel rebar. This article aims to determine the appropriate loading rate that complies with ASTM and SNI.

2. Method
This study using deformed bar BJTS 40, which diameter has been reduced. Moreover, all samples are random samples with different quality, specification, type, and brand of steel rebar. There are 6 samples for each deformed bar D8, D10, and D12 mm and 1 sample for deformed bar D13 mm. Each sample has length ($l_0$) which varied from 40 to 65 mm.

Tension test was done using UTM Gotech machine and according to SNI 07-2529-1991 [1] and ASTM A370 [6] with three different kinds of loading rate: 7 MPa/s, 20 mm/min, and 1 mm/min. 1 sample of deformed bar D13 mm using 7 MPa/s and every 3 samples of deformed bar D8, D10, and D12 mm using 20 and 1 mm/min.

3. Results and discussions
The results will be discussed in three subsections, which divided based on the stress rate: 7 MPa/s, 20 mm/min, and 1 mm/min.

3.1. Test using 7 MPa/s of stress rate
A tensile test was performed with 7 MPa/s of stress rate on deformed bar D13 as shown in Figure 1. Loading rate of 7 MPa/s was chosen randomly between range of ASTM (1.15 – 11.5 MPa/s). There was only one sample using loading rate of 7 MPa/s presented in Figure 1 because the other samples were not eligible to use due to their failure mode. The result of deformed bar D13 showed that the stress rate still acceptable according to SNI. However, according to ASTM, this test with 7 MPa/s of loading rate indicates difficulties of the machine in maintaining the speed of the testing machines in the post-limit of elastic (yield stress) due to a long duration of test, which was 81 minutes and 35 seconds. It took long duration because apparently the loading rate of 7 MPa/s was not only applied on elastic region, but also applied on the post elastic limit (after yielding phase to failure point), which caused a very small increase of strain. Due to a long duration of test, other loading rates were used to compromise the loading rate requirements and duration. Nevertheless, this sample failed in the middle of rebar with the shape of cup-and-cone fracture as shown in Figure 2. Result of fracture mode for deformed bar D13 is in accordance with usual fracture mode of steel bars.
Figure 1. Stress-strain curves of sample deformed bar D13 A1-3 using 7 MPa/s of stress rate.

(a)  
(b)  

Figure 2. Mode of failure using 7 MPa/s of stress rate.

3.2. Test using imposed displacement 20 mm/min

Another campaign of tensile test was done using 20 mm/min of imposed displacement rate on deformed bar D8, D10, and D12 mm. Loading rate of 20 mm/min was designated because this loading rate was used before on the previous machine in our laboratory. Thereby, loading rate of 20 mm/min was chosen to operate on the new machine to evaluate whether this loading rate was in accordance with SNI and ASTM about speed of testing or not. The result of stress-strain curve for each diameter of deformed bar was put together, as shown in Figure 3, to compare every samples within the group and outside the group by comparing it to result of 7 MPa/s to observe the tendencies of each sample. For stress-strain comparison, the author can only study Figure 3(c) since they have the closest bar diameter. As the sample of the bars are taken randomly neither from the same bar nor specification, the author could not see the effect and comparison of yield stress, strain capacity, and stress capacity. Nevertheless, in terms of slope (or stiffness) of the curves and the trend, Figure 3(c) show the same condition and no significant differences. Moreover, investigation on the stress rate of tensile test on one half of yield stress is summarized in Table 1. The beginning rate of stress is larger than 100 MPa/s, which above interval 1.15-11.5 MPa/s of ASTM E8M and above 10 MPa/s of SNI 07-2529-1991 standards. Briefly, tensile test’s result of loading rate of 20 mm/min showed larger rate of stress compared to SNI and ASTM. Therefore, it is necessary to find the most possible imposed displacement rate to control the loading on the steel bar. Nevertheless, the rates of stress post yielding are appropriate to ASTM E8M standard (0.05-0.5 def/min). Then, as shown in Figure 4, samples failed in the middle of rebar, where the machining process occurred. Samples exhibited dominant cup-and-cone fracture with little influence of shear, which still following the usual fracture of steel bars.
Table 1. List the average stress rate from the beginning up to one-half of the yield stress.

| Sample | D0 (mm) | Speed Test before a yield (MPa/s) | Speed Test after yield (def/min)* | Duration of Test (min) |
|--------|---------|----------------------------------|----------------------------------|------------------------|
| A1-3   | 7 MPa/s | 13.71615                         | 0.003844                         | 81.58667               |
| A0-0   | 12      | 103.6356                         | 0.333619                         | 1.061917               |
| A0-2   | 12.6    | 112.9242                         | 0.333625                         | 0.919583               |
| B0-0   | 8       | 209.4886                         | 0.524952                         | 1.008083               |
| B0-1   | 8       | 207.3405                         | 0.526500                         | 0.901083               |
| B0-2   | 8       | 178.2431                         | 0.525629                         | 0.943417               |
| C0-0   | 10      | 169.2909                         | 0.420981                         | 0.879667               |
| C0-1   | 10      | 172.1385                         | 0.421352                         | 0.871917               |
| C0-2   | 10      | 177.9525                         | 0.421036                         | 0.848167               |

* Speed test after yield is obtained from the evaluation from recorded result of the machine (stress and strain), which there is no standard conversion.

Figure 3. Stress-strain curves using 20 mm/min of stress rate on deformed bar sample (a) D8, (b) D10, and (c) D12.
3.3. Test using imposed displacement 1 mm/min

Another tensile test was done using 1 mm/min of imposed displacement rate on deformed bar D8, D10, and D12 mm. Loading rate of 1 mm/min was chosen due to the studies on the recorded results of the test. Using this loading rate, the stress rate is still in the regulated interval according to ASTM E8M. Same as section 3.2, Figure 5 was made to compare every samples within the group and outside the group by comparing it to result of 7 MPa/s. Same as section 3.2, the bars used are random samples, which were neither from the same bar nor specification. In terms of slope of the curves, Figure 5(c) shows the same trend except for Sample A1-0 D12 mm. Moreover, investigation on the stress rate of the tensile test from the beginning of the test to one half of yield stress is summarized in Table 2. All stress rates before yield are in the allowable interval 1.15-11.5 MPa/s according to ASTM E8M and below 10 MPa/s of SNI 07-2529-1991 standards except for Sample B1-1 D8 mm. Then, further studies on post yielding phase show that speed tests after yielding are not in allowable interval 0.05-0.5 def/min according to ASTM E8M. Nevertheless, sample loading using 1 mm/min has a good speed on the area before yielding. Same as section 3.2, samples failed in the middle of rebar and exhibited dominant cup-and-cone fractures with little influence of shear as shown in Figure 6.

Table 2. List the average stress rate from the beginning up to one-half of the yield stress.

| Sample | D0 (mm) | Speed Test before a yield (MPa/s) | Speed Test after yield (def/min)* | Duration of Test (min) |
|--------|---------|---------------------------------|----------------------------------|----------------------|
| A1-3 7 MPa/s | 13 | 7 | 0.003844 | 81.58667 |
| A0-0 | 12 | 5.071827 | 0.016649 | 20.26225 |
| A0-1 | 12.6 | 3.842790 | 0.003844 | 19.53483 |
| A0-2 | 12.6 | 3.412293 | 0.015856 | 21.11233 |
| B0-0 | 8 | 9.994142 | 0.024976 | 15.16517 |
| B0-1 | 8 | 10.16662 | 0.024976 | 17.23233 |
| B0-2 | 8 | 9.974437 | 0.024974 | 17.34958 |
| C0-0 | 10 | 5.999851 | 0.019979 | 19.59367 |
| C0-1 | 10 | 6.972853 | 0.01998 | 17.34958 |
| C0-2 | 10 | 6.959316 | 0.01998 | 17.57017 |

* Speed test after yield is obtained from the evaluation from recorded result of the machine (stress and strain), which there is no standard conversion.
Figure 5. Stress-strain curves using 1 mm/min of stress rate on deformed bar sample (a) D8, (b) D10, and (c) D12.

Figure 6. Mode of failure using 1mm/min of stress rate.
4. Conclusions

Random samples with difference of quality, specification, and brand of steel reinforcement bar were used in this research; therefore, the value of yield stress, stress capacity, and strain capacity are not the main discussion in this paper. Nevertheless, in terms of slope of the curves, samples with closest diameter to deformed bar D13 shows the similar trends. Besides, investigation on the stress rate of the tensile test to one half of yield stress is summarized in this research. Then, the author did not convert the speed test after yield. However, the author evaluated the recorded result of tensile test from the machine.

Using the previous loading rate from the previous machine in the lab, which was 20 mm/min, this loading rate results in a very large stress rate at the beginning (before yielding). It exceeds largely from the limit of stress from ASTM E8M and SNI 07-2529-1991. This displacement rate is proper to use if the ultimate strength is the point of interest to be obtained. The difference to the limit of allowable stress rate is very big. The smallest stress rate is 9 times the allowable limit whilst the largest one is 18 times the allowable limits (11.5 MPa/s). However, the post yielding rate fulfils the requirement according to ASTM E8M. This displacement rate is proper to use if the ultimate strength is the point of interest to be obtained.

Using the speed test of 1 mm/min results in sufficient stress rate before yielding. It is appropriate according to ASTM E8M and SNI 07-2529-1991. After the yielding, by using the same imposed displacement rate, the strain rate itself did not suitable according to ASTM E8M. In other words, this displacement rate is suitable to use to find the yielding point. Nevertheless, the difference in the limit of strain rate is not extremely big. The smallest and largest strain rate are 0.016 and 0.025, while the lower limit of the strain rate is 0.050.

So, to test the stress bar using UTM Gotech in our laboratory, the author needs to choose the point of interest to determine the proper loading rate, in MPa/s or imposed displacement. Furthermore, in the civil engineering area of concrete design, the most important value is the yielding point of the steel bar. Therefore, choosing the allowable loading rate closer to the ASTM E8M and SNI 07-2529-1991, precisely in predicting the yielding point of the steel bar, seems legitimate. Moreover, the difference is not extreme for the post yielding phase.

All samples of steel rebar failed in the middle of samples, where the diameter has been reduced, and failed with failure mode of cup-and-cone fracture. Some samples are a little bit influenced by shear; however, those samples still showed a dominant cup-and-cone fracture. Therefore, the mode of failure of all samples is following the usual fracture of steel bars.

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