Challenges in Assessing the Precision of High Strain Rate Testing for UHPC

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Abstract: High strain rate testing of UHPC is commonly performed using the split-Hopkinson pressure bar (SHPB). Past SHPB testing has shown considerable scatter in the dynamic strengths achieved. To determine how much of this variation is due to the material, and how much is introduced by the SHPB, a Gage R&R study was performed. If a significant amount of variation is introduced by the SHPB itself, that raises questions about the value of using or making comparisons with data collected with the SHPB. Applying Gage R&R to a destructive measurement technique presents several challenges because repeat measurements are not possible. The use of alternate study setups was considered. However, it is inevitable that some material variance will be attributed to the measuring system. The Gage R&R will therefore give an upper bound on the measurement error. Gage R&R analysis was also applied to data from wood and normal strength concrete tests on the same SHPB instrument. By using materials with reduced variability, a more realistic estimate of measurement error was obtained.

Keywords: Gage R&R; SHPB; Ductal; Cor-Tuf; Measurement System Analysis

1. Introduction

There is often a large amount of scatter in data from dynamic compression tests of UHPC. Some of this variability is to be expected, as it is impossible to produce identical concrete specimens. At high strain rates, voids, fiber distribution, end planeness, and end parallelness can all have an effect on failure strength. However, no measurement system is perfect, and the instrument used for testing, the split-Hopkinson pressure bar (SHPB), also contributes to the error. To determine the magnitude of this error, a Gage Repeatability and Reproducibility (Gage R&R) study is commonly used. Gage R&R has its origins in statistical quality control. If measurements are used for evaluating a process or for accepting/rejecting finished parts, it is important to know that the measurements are reliable (Ackermann 1993).

Michigan Tech has a 3-in. (7.62-cm) diameter SHPB that has been used in research projects to test multiple UHPCs, as well as normal strength concrete (NSC), wood, and metal. Previous works showed a high variation in measured failure strengths of UHPC (Clark 2013; VanSlembrouck 2015). Because of this, there was concern that the SHPB equipment or the data acquisition (DAQ) system might be faulty. To determine how much the equipment was contributing to the measured variation, a Gage R&R analysis was undertaken.

2. Background

2.1. Split-Hopkinson Pressure Bar

Some familiarity with the principles of the SHPB is assumed, as the length of this paper does not permit a detailed discussion. At its most basic, the SHPB consists of two long, elastic bars (termed the input and output bars) with a specimen sandwiched between them. This setup is illustrated in Figure 1. An elastic stress wave is propagated through the input bar, loading the specimen. The stress wave is generally produced by a striker bar launched from a compressed-gas cannon. Part of this stress wave is transmitted through the specimen to the output bar, and part is reflected back into the input bar. Strains in the bars are measured using strain gages and recorded by a DAQ system. Based on classical one-dimensional wave propagation theory, the stress, strain, and strain rate in the specimen may be calculated from the recorded strains. All data used in this analysis were calculated using the "one-wave" method, which assumes that the specimen is in force equilibrium. For additional details, refer to Gama, Lopatnikov, and Gillespie (2004), who provide a thorough introduction to the SHPB and a critique of the underlying assumptions.

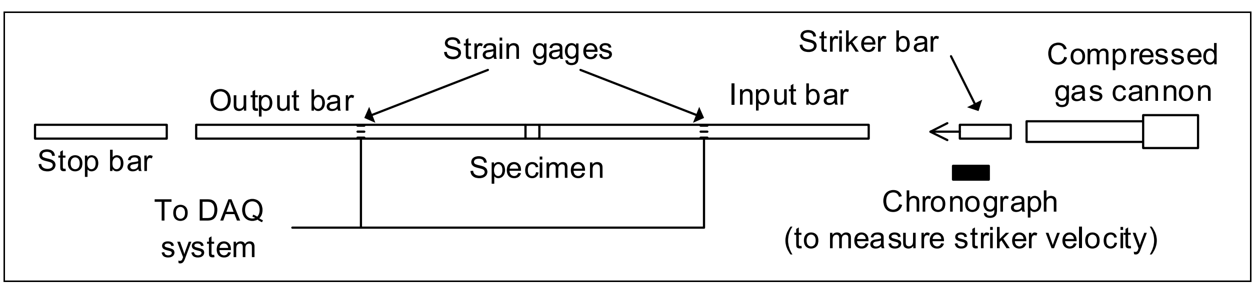

Figure 1. Diagram of the SHPB setup

2.2. Gage R&R for Destructive Measurements

A traditional Gage R&R involves selecting a number of representative parts to be measured. Several different operators measure these parts using the same gage, with each part being measured multiple times. The order of the measurements is often randomized. Replicate measurements of each part allow repeatability error (differences between measurements by the same operator) and reproducibility error (differences between measurements by different operators) to be determined. Statistically, the total variance σ^2 is the sum of material (or part-to-part) variance σ_m^2, equipment variance σ_e^2, and operator variance σ_o^2, as shown in equation (1):

$$\sigma^2 = \sigma_m^2 + \sigma_e^2 + \sigma_o^2 \quad (1)$$

The total variance due to measurement is $\sigma_e^2 + \sigma_o^2$. This is also called the Gage R&R and can be represented as a percent contribution to the total variance:

$$\%\text{ Gage R\&R} = \frac{\sigma_e^2 + \sigma_o^2}{\sigma^2} \times 100\% \quad (2)$$

The Gage R&R study involves some assumptions that are easily satisfied by this traditional setup: the measured quantity does not vary over time, and the measurement does not alter the part in any way (De Mast and Trip 2005). The first assumption is essentially true for SHPB tests of UHPC, provided the specimens have cured long enough that additional strength gain over time is negligible. The second assumption presents an issue. Testing fractures the specimen, so repeated measurements are impossible. To address this, De Mast and Trip (2005) suggested several alternate methods. First, identical parts could be used. Second, if the parts to be tested are not identical, but the measurement of interest varies in a known way, this may be corrected for. Third, the destructive measuring process could be compared to a non-destructive process if one is available. Fourth, if only destructive testing is possible, but another machine can make very precise destructive measurements, it may be used to determine the material variance. In practice, it may turn out that none of these alternate methods can be implemented perfectly: e.g., instead of completely identical parts, only parts with very low variance are available. Typically, when the assumptions are imperfectly satisfied, the material variance also contributes to the measurement variance (Ackermann 1993; De Mast and Trip 2005). The result is an artificially high Gage R&R.

3. Testing Methods

The analysis consisted of two steps: obtaining data from previous SHPB testing at Michigan Tech, and performing a Gage R&R study on an appropriate selection from each data set.

3.1. Data Selection

All data used in this analysis were collected in previous research using Michigan Tech's 3-in. (7.62-cm) diameter SHPB. The data sets used were from testing of two UHPCs (Cor-Tuf and Ductal®), NSC, and maple. Because the research was primarily carried out for theses or dissertations, most, if not all, tests for each material were performed by one operator.

The following subsections describe the specimen data for each material. The original researchers' specimen IDs are used throughout. While the naming schemes are all slightly different, it was thought that this small inconsistency was justified by the ease of comparing with the original works. Finally, a small (n = 12) data set from high strain rate compression testing of aluminum alloys was available, but was not large enough to be statistically useful.

3.1.1. Cor-Tuf

VanSlembrouck (2015) performed dynamic compression tests on Cor-Tuf, a UHPC developed by the US Army Corps of Engineers. VanSlembrouck's research looked at the effects of cure regime and specimen aspect ratio (length divided by diameter). The different groups of specimens were assigned IDs beginning with "C-U-" to indicate Cor-Tuf UHPC, followed by "TT" for thermal-treat cure or "AMB" for ambient cure, and a letter to indicate the aspect ratio: "A" for 0.5, "B" for 1, and "C" for 2. For the Gage R&R study, all data were from tests carried out with a cannon pressure of 80 psi (552 kPa). In all, 6 groups of 6 specimens were selected.

3.1.2. Ductal

Clark (2013) performed dynamic compression tests on Ductal®, a UHPC from Lafarge North America. Clark also considered the effects of cure regime and specimen aspect ratio. Group IDs began with "U-" to indicate UHPC, followed by "A," "B," or "C" to indicate an aspect ratio of 0.5, 1, or 2, respectively. Finally, the cure regime was identified by "TT" for thermal-treat cure or "AMB" for ambient cure. Because there were only 3 specimens each for U-C-AMB and U-C-TT, these were excluded from the Gage R&R study. All tests were carried out with a cannon pressure of 80 psi (552 kPa). In all, 4 groups of 7 specimens were selected.

3.1.3. NSC

Vitton, Subhash, and Dewey (2002) examined the effect of aggregate type and moisture condition on dynamic compression of NSC. Three-inch (7.62-cm) diameter, 6-in. (15.24-cm) long cores were taken from five batches, each incorporating a different aggregate type. Groups were designated by batch number (1–5) and test condition, wet or dry. Batch 2–dry only had 4 specimens, and was excluded from the Gage R&R study. The program WebPlotDigitizer v3.8 (Rohatgi 2015) was used to generate numerical values from a plot of data, as only a scanned hardcopy was available. In all, 9 groups of 5 specimens were selected.

3.1.4. Maple

Gilbertson (2011) performed dynamic compression tests on maple and pine, with specimens taken in the longitudinal, radial, and tangential directions. For this analysis, only maple longitudinal specimens were used. Group IDs began with "ML," followed by the diameter in tenths of an inch, and the cannon pressure in psi. Two diameters were used, 2.5 in. (6.35 cm) and 3.0 in. (7.62 cm). Cannon pressures ranged from 20 psi (138 kPa) to 60 psi (414 kPa). In all, 6 groups of 5 specimens were selected.

3.2. Gage R&R Calculations

All calculations were performed using Minitab 17 Statistical Software (Minitab 2010). The measurement system analysis was carried out using the Gage R&R Study (Crossed) command and the ANOVA method. It would have been more correct to perform calculations as a Nested Gage R&R Study, as each part was only tested by one operator; however, with only one operator in each study, this distinction is unimportant. The "Nested" command treats having one operator as an error in setup, so the "Crossed" command was used. The measurement considered was the maximum calculated stress. For each material, the data was divided into groups, with the parts (i.e., specimens) in each group having the same dimensions and test parameters. A balanced design was required, so groups were selected to have an equal number of parts, attempting to pick representative values for each group. Because repeated measurements are impossible, parts within each group were assumed to be similar enough to consider them the same part. Each material was tested by one operator, so reproducibility could not be determined.

In this test setup, the material variance σ_m^2 from equation (1) is the variance *between* groups. Because the parts (specimens) in each group are not completely identical, there is also some variance σ_g^2 *within* each group. Assuming that the parts are completely identical implies that $\sigma_g^2 = 0$, which the following results will show to be untrue. This is the greatest weakness of Gage R&R when applied to destructive measurements.

4. Results

Gage R&R results for the Cor-Tuf specimens are shown in Figure 2 below. The Gage R&R component of the variation ("% Contribution" in Figure 2*a*) is quite high, contributing 71.2% to the total observed variation. This implies that the actual variation in the specimens is only responsible for 28.8% of the observed variation. If this were the case, it would cast serious doubt on the usefulness of the SHPB for testing. However, recall that for Gage R&R with destructive testing, it must be assumed that a number of specimens are identical enough to be considered one specimen. As shown in part *b* of Figure 1, there is a large amount of variation for specimens prepared and tested in the same way: group C-U-TT-A, in particular, has a range of nearly 28 ksi. Although thermal treatment has been shown to increase the quasistatic compressive strength of UHPC, VanSlembrouck (2015) concluded that cure regime has no significant effect on the dynamic strength of Cor-Tuf at a 95% confidence level. At aspect ratios of 1 and 2 ("B" and "C" specimens, respectively), the thermal treatment does increase the strength somewhat, though the strength seems to decrease with thermal treatment at an aspect ratio of 0.5 ("A" specimens).

Note that, if one looks at the percent study variation bars ("% Study Var" in the figure below), the quantities are different than those for the percent contribution bars. This is because study variation is calculated based on standard deviations, rather than variances. As a result, the % Study Var numbers do not add up to 100%.

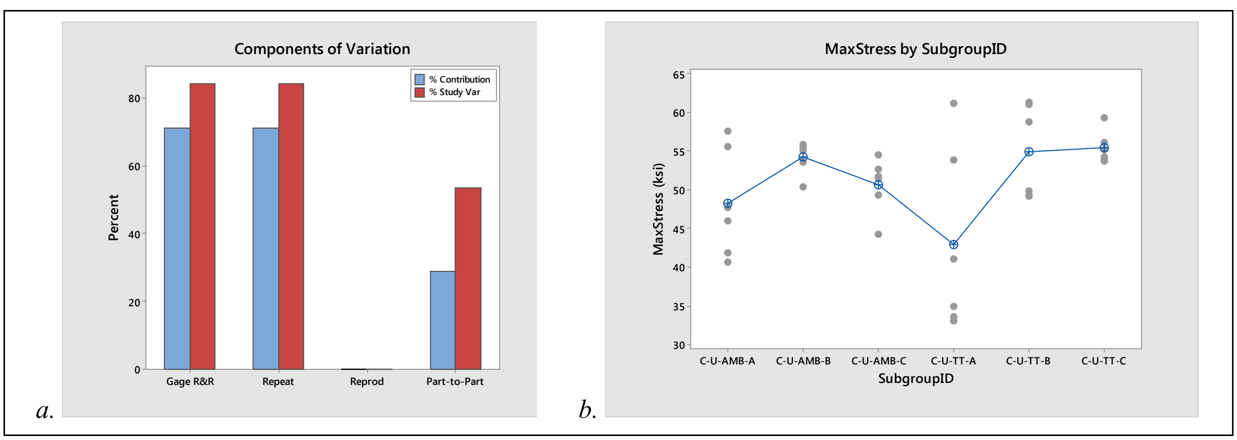

Figure 2. ***a*. Gage R&R results for Cor-Tuf. *b*. Plot of maximum stress by group. Note: 1 ksi = 6.895 MPa**

Gage R&R results for Ductal are shown in Figure 3. The analysis attributes all observed variation to the measuring system, hence a Gage R&R contribution of 100%. Again, although thermally-treated Ductal does have a higher quasistatic strength than ambient-cured Ductal (21.1 ksi vs. 18.8 ksi, or 145 MPa vs. 130 MPa), the same trend is not clearly present in the dynamic results (Clark 2013). As these two analyses have shown, data from UHPC testing has such high variation that the assumption of identical specimens is questionable at best. It was decided to use data with less variation to better satisfy this assumption.

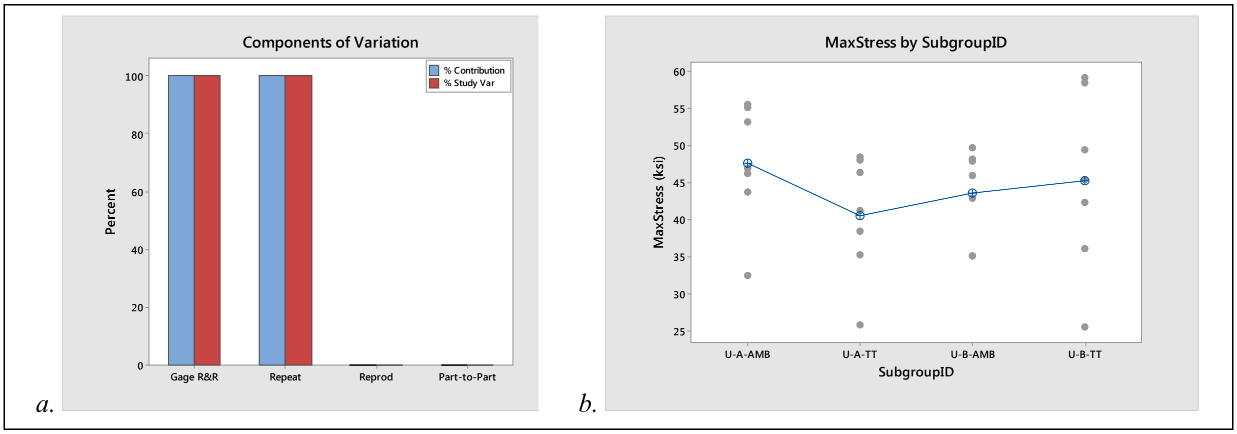

Figure 3. *a*. Gage R&R results for Ductal. *b*. Plot of maximum stress by group. Note: 1 ksi = 6.895 MPa

Gage R&R results for NSC are shown in Figure 4. In this case, only 43.9% of the total variation is attributed to the SHPB. A guideline is that a measurement system is considered acceptable when Gage R&R is below 1%, and marginally acceptable for values between 1% and 9%. While not ideal, this result indicates that the SHPB is not as imprecise as the analyses run on UHPC data would suggest.

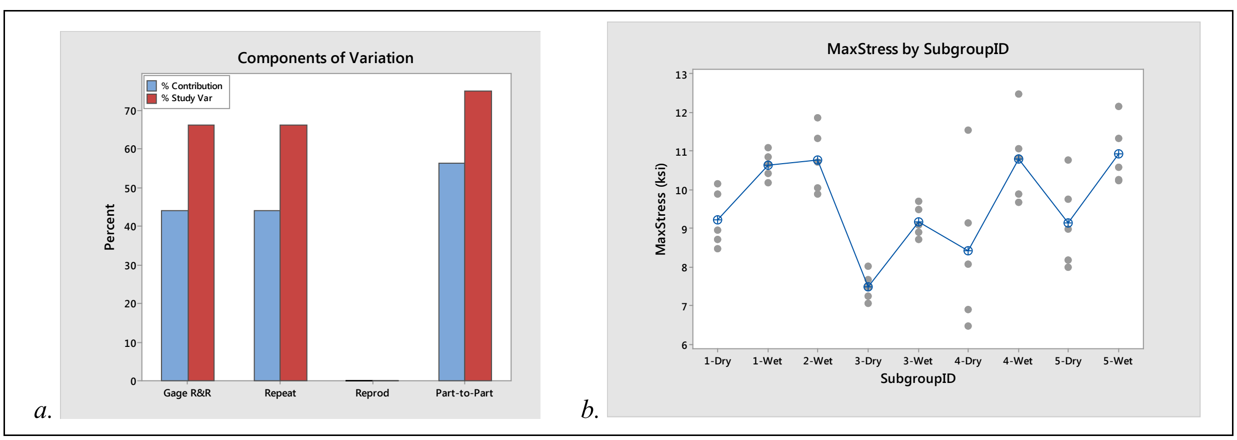

Figure 4. *a*. Gage R&R results for NSC. *b*. Plot of maximum stress by group. Note: 1 ksi = 6.895 MPa

Finally, Gage R&R results for maple are shown in Figure 5. The Gage R&R contribution is 36.9%. Notice the spread shown in the "MaxStress" subplot. While the maple data has less scatter than the UHPC or NSC, it is still far from the ideal, completely identical specimens that could be used to determine the "true" value of Gage R&R. Thus, the Gage R&R of 36.9% can be considered an upper bound on the "true" value.

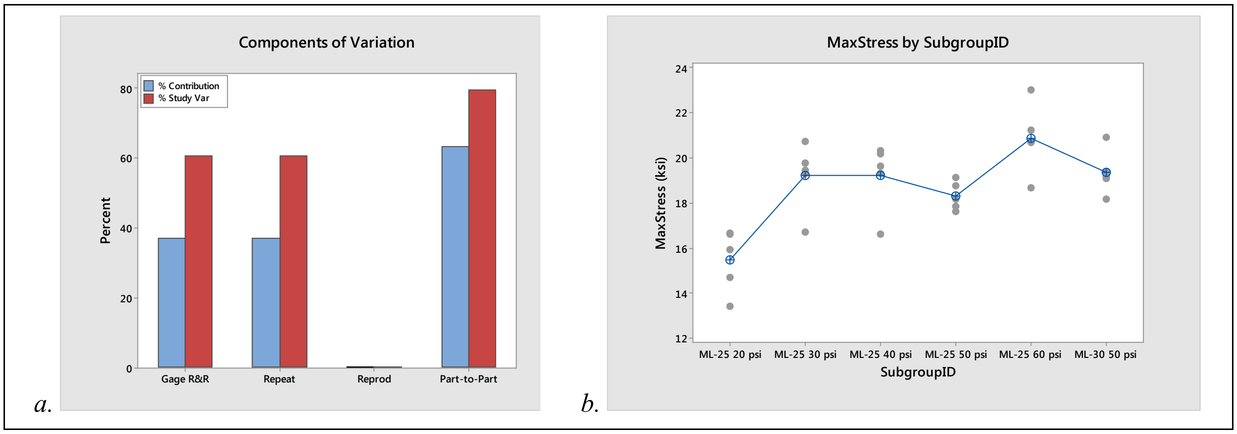

Figure 5. *a*. Gage R&R results for maple. *b*. Plot of maximum stress by group. Note: 1 ksi = 6.895 MPa

5. Discussion

Gage R&R results and descriptive statistics for the four data sets are summarized below in Table 1. Qualitatively, there is a decrease in Gage R&R with decreasing coefficient of variation (COV). To understand this, consider a data set comprising several groups. If the variation of the entire data set is high, the variation within each group should be high as well, and vice versa. This assumes that the groups are representative. Recall that the destructive Gage R&R analysis is founded on the assumption that the specimens within each group are identical. Thus, differences in measured values between the specimens are assumed to come from the measurement system. If the specimens are not identical, then the variation in the specimens themselves is attributed to the measurement system. Hence, the apparent Gage R&R should decrease with decreasing material variance *within* groups.

Table 1. Summary of Gage R&R analyses. Note: 1 ksi = 6.895 MPa

Data Set	Cor-Tuf	Ductal	NSC	Maple
Gage R&R (% contribution)	71.2	100.0	43.9	36.9
Part-to-part (% contribution)	28.8	0.0	56.1	63.1
Average (ksi)	51.04	44.23	9.62	18.72
St. Dev. (ksi)	7.47	8.78	1.48	2.06
COV (%)	14.6	19.9	15.4	11.0

Scatter in SHPB tests of UHPC may also be compared to scatter from similar UHPC specimens tested quasistatically. The 28-day quasistatic compressive strengths of Cor-Tuf and Ductal control specimens are given in Table 2. Typically, three cylinders were tested for each UHPC and cure regime. The COV for both UHPCs was between 6% and 19%, depending on curing method. Given this scatter, it does not seem unreasonable that dynamic strengths should have a COV of 15% or 20%; however, care should be exercised due to the small sample size for quasistatic tests.

Table 2. Quasistatic compression test data (Clark 2013; VanSlembrouck 2015). Note: 1 ksi = 6.895 MPa

UHPC	Cor-Tuf		Ductal	
Cure Regime	AMB	TT	AMB	TT
N	5	3	3	3
Average (ksi)	25.89	26.27	18.79	21.12
St. Dev. (ksi)	4.83	1.72	1.28	3.79
COV (%)	18.7	6.5	6.8	18.0

This analysis differed from a typical Gage R&R in a production environment. Generally, a quality engineer would decide to perform a Gage R&R analysis, then collect a representative sample of manufactured parts. In this case, the study was undertaken only after all of the data had been collected. Data used in this study were collected for characterization of dynamic mechanical properties, not for a Gage R&R study. More data points would have improved the study, but it is expensive and time-consuming to fabricate and test SHPB specimens.

The greatest limitation is that a Gage R&R study on a destructive measuring process can never truly separate material variation from measurement variation. Because replicate measurements are impossible, it is necessary to assume that multiple tests on different specimens are similar enough to be considered multiple tests on *the same specimen*. This assumption was not satisfied for any of the materials examined, least of all for the UHPCs.

Some sources of experimental error for the UHPC tests are briefly discussed here. Two of these are related to confinement, which is particularly important for UHPC as it is hydrostatic stress-dependent. First, friction between the specimen and the bar restrains the expansion of the specimen, providing confinement. Numerical simulations by Li and Meng (2003) suggest that frictional confinement has a significant effect on the measured strength when the coefficient of friction is 0.2 or greater. Second, inertia also confines the specimen's radial expansion, and has been shown to contribute to the strength increase at high loading rates (Zhang et al. 2009). The confining stress from radial inertia varies with the strain acceleration, $\mathrm{d}^2\varepsilon/\mathrm{d}t^2$, which is a characteristic of the applied loading. However, the SHPB only permits open-loop testing. The loading is affected by the choice of striker bar, pulse shaper, and the striker bar's impact velocity, which is controlled by altering the cannon pressure. Prior to each test, the cannon is filled from a gas cylinder, reading the pressure from a gage. This introduces some variability into the pressure used, and hence the loading for each specimen. At an aspect ratio of 1, the strain rates achieved were 147–553 s^{-1} for Cor-Tuf and 144–308 s^{-1} for Ductal (VanSlembrouck 2015; Clark 2013). Finally, specimen end planeness has a significant effect on results for UHPC, but not for NSC (Clark 2013). Non-planar ends result in stress concentrations as the load is applied unevenly.

6. Conclusions

This study was performed to determine whether the scatter observed in UHPC data was due to material variability, or if it indicated an equipment issue. Preliminary calculations suggested that Gage R&R could be as high as 71% or even 100%. Gage R&R studies on NSC and wood, however, showed that the actual measurement error was not as high as originally thought. The Gage R&R of roughly 37% from the study on maple specimens can be viewed as an upper bound on the "true" Gage R&R. Because the test is destructive, it is inevitable that some material variation will be identified as measurement variation. This is the fundamental challenge in using Gage R&R on a destructive test.

The Gage R&R results in this paper suggest that there is no reason to suspect that previous UHPC tests at Michigan Tech were invalid due to faulty equipment. The measurement error of Michigan Tech's SHPB has been given an upper bound here; the actual measurement error may in fact be lower, but there is no way of assessing that by Gage R&R analysis on the data currently available. Results also indicated that UHPC specimens prepared and tested in the same manner may nevertheless have a wide range of failure strengths under dynamic compressive loading.

A better method for determining the Gage R&R would be to test specimens, such as metals, that have very low variability in failure strength. If the same procedure is followed as when testing UHPC, this should result in a Gage R&R that is close to the "true" value. A lower-cost alternative to this suggestion might be performing a series of bars-apart and bars-together calibrations, and analyzing the measured strains. No specimen is being measured, so this would provide information about the instrument and operator only. This alternate setup might require changes in the statistical procedure used. If improved Gage R&R study setups such as these prove unsuccessful, it may indicate that another statistical technique should be used for assessing the precision of SHPB tests.

7. References

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