The Effect of Injurious Whole Rib Loading on Rib Cortical Bone Material Properties

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Abstract Finite element models can be used to evaluate thoracic injury mitigation strategies during a motor vehicle collision; however, matched structural and material properties for ribs are needed to validate these models. While it is possible to obtain material properties from ribs that have already undergone structural testing, it is unknown to what degree the material properties may be altered. Therefore, the purpose of this study was to quantify the tensile material properties of previously fractured ribs and compare them to the material properties of unloaded ribs from the same individuals. The sixth rib from 18 subjects underwent a whole rib bending test, resulting in fracture. Cortical bone from both the fractured and contralateral (control) ribs underwent tension coupon tests to quantify the material properties. Only yield stress and yield strain were significantly different between the fractured and control ribs. Consequently, it may be possible to estimate the pre-failure modulus, failure strain, failure stress, and strain energy density of the cortical bone from a rib after a structural test. However, due to the limited sample size and variance within an individual, additional testing is needed to more thoroughly evaluate how injurious loading affects material properties along the length of a rib.

Keywords post-yield, rib fracture, thorax injury

I. INTRODUCTION

The chest is one of the most frequently injured body regions in motor vehicle collisions (MVCs). In a study of the National Automotive Sampling System Crashworthiness Data System (NASS-CDS) from 1993 to 2004, 80% of AIS4+ injuries sustained by United States drivers were to the head and chest [1]. Sustaining AIS3+ rib fractures in a MVC significantly increases a patient's in-hospital mortality risk [2]. Additionally, older adults who suffer severe rib fractures during a MVC are 2.5 times more likely to succumb to their injuries [2].

Finite element models are useful tools to evaluate the effectiveness of thoracic injury mitigation strategies. However, finite element models require validation data, such as subject-specific structural and material properties. While structural tests, such as rib bending tests or thoracic impact tests, require most if not all of a rib, material testing only requires a small section of bone. Therefore, it is possible to obtain cortical bone material properties from a rib that has already undergone structural testing, given that the necessary amount of intact cortical bone remains. This would increase the amount of validation data available for finite element models and decrease the amount of bone material needed to derive both structural and material properties. However, it is currently not known whether the loading experienced during structural tests affects rib cortical bone material properties.

Previous studies have shown that the moduli of cortical bone coupons decrease after being loaded beyond the yield point [3-6]. Consequently, any intact bone remaining after a structural test may have altered material properties, if the bone was loaded beyond the yield point. Unfortunately, previous studies did not evaluate how loading beyond the yield point affected other material properties apart from the modulus. Additionally, some of these studies were performed at lower strain rates (0.001 strain/s) than what would be experienced during an MVC or other traumatic event. Therefore, their results may not be valid at higher strain rates [4][5]. Therefore, the purpose of this study was to quantify the tensile material properties of previously fractured ribs at a strain rate representative of thoracic belt loading during a MVC and compare them to the material properties of unloaded ribs from the same individuals.

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II. METHODS

Paired sixth ribs from 18 individuals (10 male, 8 female), ranging from 35 to 99 years of age (mean: 73.2 ± 17.7 years), were included in this study. The ribs were ethically obtained through the Body Donation Program at The Ohio State University and Lifeline of Ohio. The left or right rib was randomly selected to undergo a whole rib anterior-posterior bending test intended to simulate a frontal thoracic impact with a strain rate of approximately 0.5 strain/s [7-9]. During the bending test, the sternal end of the rib was impacted at approximately 2 m/s, causing it to translate toward the vertebral end. Thus, the cutaneous cortex of the rib was loaded in tension. All bending tests resulted in at least one fracture along the length of the rib. Cortical bone from the ribs that sustained fractures during the bending tests as well as the contralateral, untested (control) ribs underwent tension coupon tests to quantify the material properties. The details of the tension coupon preparation, testing, and data analysis are presented in the following sections. Material properties for some of the ribs were previously reported [10].

Specimen Preparation

Dog-bone coupons were fabricated and tested according to the methodology presented in [10-12]. Rectangular sections of the cutaneous cortical bone, measuring 30 mm long and 9 mm wide, were cut from the ribs using a custom-made low-speed circular saw with a diamond encrusted blade. The samples were obtained from the anterior, lateral, and posterior regions of the rib since previous studies have found no significant difference in cortical bone material properties between anatomical regions of the rib within an individual [11][12]. The specific location along the rib that the samples were cut from depended on several factors. Cortical bone was not obtained posterior to the angle of the rib or within an inch of the transition to costal cartilage. Additionally, locations with minimal natural curvature and sufficient width to accommodate a coupon were targeted. For the fractured ribs, an effort was made to obtain cortical bone as far from the fracture as possible. Finally, all samples were aligned with the main axis of the rib. If a rib was not wide enough to accommodate a sample 9 mm in width, the sample was cut to the maximum possible width. After cutting, the sample was wet sanded to a uniform thickness using decreasing grits of sand paper (240, 320, 400, and 600). The sample was then milled into a dog-bone shape using a Computer Numerical Control (CNC) mill (MAXNC 10, Ximotion LLP, Gilbert, AZ, USA) (Figure 1). Lastly, the coupons were sanded to a final thickness, which was uniform within ± 0.0127 mm across the entire coupon.

Tension Tests

Each coupon underwent a uniaxial tensile test on a high rate servo-hydraulic Material Testing System (810 MTS, Material Systems Corporation, Eden Prairie, MN, USA) (Figure 2). The coupons were pulled in tension past the point of failure. A custom slack adapter was used to maintain a constant strain rate of approximately 0.5 strain/s. During testing, the coupons were held in place using custom designed grips, which were aligned before testing to ensure the coupons experienced a purely tensile load [11][12]. An extensometer (632.13F-20, Material Systems Corporation, Eden Prairie, MN, USA) measured the change in length of the gauge length, while a uniaxial load cell (1500ASK-100, Interface, Scottsdale, AZ, USA) measured the tensile force. All data were collected at 40,100.2 Hz and filtered at SAE channel filter class (CFC) 180 [13]. Strain was calculated from the extensometer output by dividing the change in length between the extensometer arms by the initial length between the arms. Stress was calculated by dividing the force by the initial cross-sectional area of the coupon gauge length, measured before the test using calipers. The yield point was calculated as the point of intersection between the stress-strain curve and a straight line at a 0.1% strain offset that was parallel to the elastic portion of the curve [14]. The elastic modulus was calculated as the slope between two points on the stress-strain curve that were approximately 10% and 50% of the yield point. The failure stress and failure strain were defined as the stress and strain at the time of failure. Lastly, the strain energy density was calculated as the integral of the stress-strain curve.

Data Analysis

Paired t-tests were used to determine whether there was a significant difference between the material properties of the fractured and control ribs. Additionally, statistical analyses were performed on the data from the previously fractured ribs to determine whether the distance between the coupon location and fracture location (distance to fracture) influenced the material properties. First, the distance to fracture and material properties were tested for normality using a Shapiro-Wilk test. Distance to fracture was not normally distributed

(W = 0.8686, p = 0.0169) so the correlation between distance to fracture and each material property was determined using the non-parametric Spearman's rank correlation (ρ). However, this correlation could be affected by inter-subject variability since it only evaluates the post-fracture material properties and does not account for the difference in material properties between the fractured and control ribs within a subject. In an effort to minimise the influence of inter-subject material property variability on the correlation results, the difference between the fractured and control material properties (difference = control - fractured) for each rib was computed. The correlation between the difference in material properties and distance to fracture was then assessed using Spearman's rank correlation. All statistical tests were performed using JMP Pro 13 (SAS Institute Inc., Cary, NC, USA) with an alpha level of 0.05.

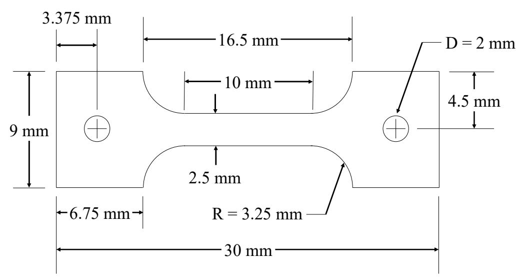

Fig. 1. Coupon schematic.

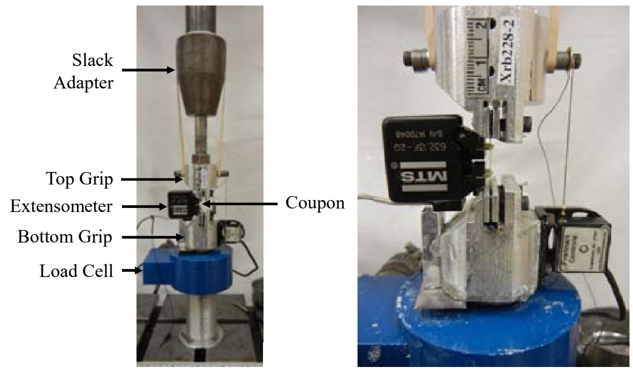

Fig. 2. Coupon tensile test setup.

III. RESULTS

Differences were observed between the material properties of the fractured and control ribs. The average modulus, failure stress, and strain energy density were slightly higher for the fractured ribs, while the average yield strain, yield stress, and failure strain were higher for the control ribs (Table I). Only the yield strain and yield stress were significantly different between the fractured and control ribs (Table I). The stress-strain curves for the fractured ribs showed a less distinct transition from the elastic to plastic regions, with yielding occurring lower on the curve compared to the control ribs (Figure 3).

The average distance between the centre of the coupon to the location of fracture on the previously tested ribs was 55.3 ± 27.8 mm (range: 17 to 131 mm). The modulus was the only material property that had a significant correlation with distance to fracture (Table II). All correlations between the fractured material property and distance to fracture were positive. However, accounting for inter-subject variation by taking the difference between the material properties of the fractured and control ribs resulted in no significant correlation with distance to fracture (Table II). Modulus, failure strain, and strain energy density experienced weak positive correlations with distance to fracture, indicating these fractured material properties decreased relative to the control material properties as the distance to fracture increased. Conversely, yield strain, yield stress, and failure stress experienced weak negative correlations with distance to fracture, indicating these fractured material properties increased relative to the control material properties as the distance to fracture increased.

TABLE I
MEASURED MATERIAL PROPERTIES AND T-TEST RESULTS

Material Property	Units	Control Average	Fractured Average	t	p-value
Modulus	GPa	12.46	13.42	1.2507	0.2280
Yield Strain	µstrain	6491	5185	5.2579	< 0.0001*
Yield Stress	MPa	69.64	59.33	3.6621	0.0019*
Failure Strain	µstrain	24444	24252	0.1945	0.8481
Failure Stress	MPa	105.67	108.65	0.9725	0.3444
Strain Energy Density	MPa-µstrain	2084269	2238447	0.7842	0.4437

* Indicates significance at p < 0.05.

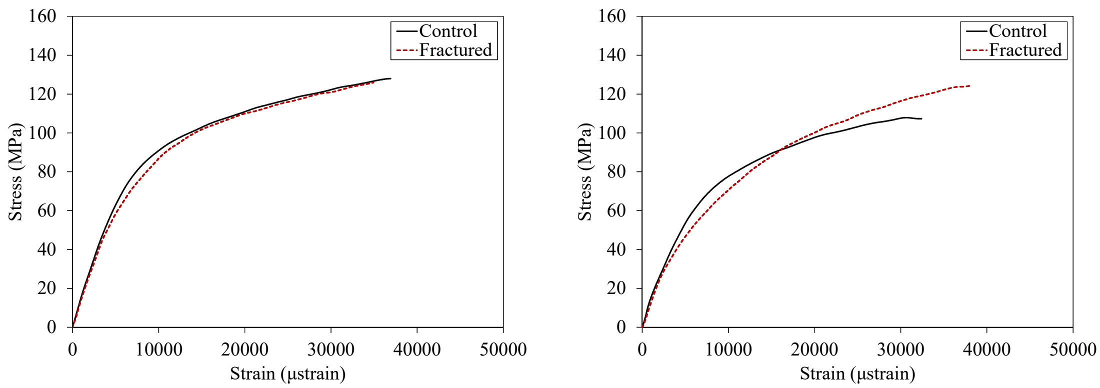

Fig. 3. Exemplar stress-strain curves from two subjects.

TABLE II
STATISTICAL CORRELATIONS WITH DISTANCE TO FRACTURE

Material Property	Fractured Material Properties		Difference Between Fractured and Control Material Properties	
	Spearman's ρ	p-value	Spearman's ρ	p-value
Modulus	0.4707	0.0487*	0.0321	0.8993
Yield Strain	0.0902	0.7219	-0.2250	0.3694
Yield Stress	0.3971	0.1027	-0.2478	0.3215
Failure Strain	0.1182	0.6404	0.0881	0.7280
Failure Stress	0.3577	0.1450	-0.2322	0.3537
Strain Energy Density	0.2291	0.3604	0.0073	0.9772

* Indicates significance at p < 0.05.

IV. DISCUSSION

The current study evaluated the difference in cortical bone material properties between intact ribs and ribs previously loaded to failure. Previous studies on human and bovine cortical bone coupons reported decreases in modulus [3][4][6], a *softening* of the yield point on the stress-strain curve [3][15], and increasing non-linearity of the stress-strain curve [4] as a result of repetitive loading. The results of the current study also showed a less distinct yield point and a smaller linear region in the stress-strain curve for the cortical bone from previously fractured ribs. However, no decrease in modulus was observed for the previously fractured ribs, which did not align with the decrease in modulus reported in the literature. It should be noted that the results of the current study are not a direct comparison to those reported in the literature since the single bending test that loaded the cortical bone in this study is inherently different from the repetitive, fatigue loading conducted on the cortical bone coupons in the literature. Additionally, the results of previous studies may be dependent on the method used to calculate the modulus. For example, [5] exposed human femur cortical bone coupons to two consecutive tensile loading cycles beyond the yield point to 0.01 strain. They reported a 33% decrease in modulus for the second loading cycle. However, the modulus was calculated using different methods for the first and second loading cycles, which may have influenced this result.

For the current study, care was taken to calculate the modulus consistently between the fractured and control ribs. For all tests, the modulus was calculated over a region of the stress-strain curve defined as 10-50% of the yield point. Since the yield point was significantly lower for the fractured ribs, the modulus was calculated over a lower range of stress and strain compared to the control ribs. In order to determine whether this difference influenced the outcome of the study, the moduli of the control ribs were recalculated over the same range of stresses as their fractured counterparts. A paired t-test was used to compare the adjusted modulus of the control ribs to the modulus of the fractured ribs and no significant difference was observed ($p = 0.4491$).

The range of the stress-strain curve used to calculate the modulus was carefully chosen to encompass the linear portions of the stress-strain curves for both the fractured and control ribs. As noted above, this linear region was smaller for the fractured ribs. If the modulus was evaluated over a higher percentage of the yield point, this would still encompass the linear region of the stress-strain curves for the control ribs, but would include part of the nonlinear region of the stress-strain curve, i.e. the area around the yield point, for the fractured ribs. Including some of the nonlinear region of the stress-strain curve in the modulus calculation for the fractured ribs would likely result in a lower modulus value. However, this would not be an accurate representation of the modulus for the fractured ribs since the modulus would be defined over a nonlinear region.

Composite materials, such as bone, typically exhibit a decreased modulus and ultimate stress after being loaded beyond the yield point [4]. Therefore, the finding that only yield stress and yield strain were significantly different between the fractured and control ribs was unexpected. A possible explanation for the lack of significance for the modulus and failure stress is that intra-subject variation confounded the results. In order to evaluate this possibility, the average absolute differences between the fractured and control ribs for each material property were compared to the intra-subject standard deviations observed in previously published tests conducted using the same test setup (Table III) [11][12]. The average absolute differences were less than the intra-subject standard deviations for all material properties except for yield stress and failure stress. This indicates that the average absolute difference between the fractured and control ribs for yield stress and failure stress exceeds the expected amount of intra-subject standard deviation. Therefore, an increased sample size may increase the statistical power enough to detect a significant difference in failure stress.

TABLE III

COMPARISON OF AVERAGE ABSOLUTE DIFFERENCES TO INTRA-SUBJECT STANDARD DEVIATIONS FROM THE LITERATURE

Material Property	Units	Average Absolute Difference Between Fractured and Control Material Properties	Intra-subject Standard Deviation from [11][12]
Modulus	GPa	2.54	3.28
Yield Strain	µstrain	1515	1609
Yield Stress	MPa	17.78	15.76
Failure Strain	µstrain	8295	9943
Failure Stress	MPa	29.54	27.59
Strain Energy Density	MPa-µstrain	1186956	1413554

Another factor to consider when interpreting the results of this study was whether the distance between the sample and the fracture location influenced the material properties of the fractured ribs. More cortical bone damage, i.e., amount of microcracks, would be expected immediately adjacent to the fracture location as opposed to several centimeters away from the fracture location. Therefore, a gradient of damage may exist along the length of the rib relative to the fracture location, such that the amount of cortical bone damage decreases with increasing distance from the fracture location. This gradient of damage would likely correspond to a gradient of material property changes, with the greatest material properties changes occurring adjacent to the fracture. When the influence of distance to fracture on the material properties was statistically assessed, a significant positive correlation was found between modulus and distance to fracture. However, this result and the lack of statistical significance for the other material properties could have been confounded by inter-subject variability, which is of particular importance since the subjects in this study spanned a wide age range. Consequently, the correlation between distance to fracture and the difference between the fractured and control material properties for each rib pair was assessed. None of the material property differences were significantly correlated with distance to fracture, which may be a result of two factors. First, it is possible that samples were taken over a range of distances that was too narrow to detect significant differences in material properties caused by a gradient of damage. Second, the coupons may have been obtained from a region of the rib that was sufficiently far from the fracture such that the cortical bone was not loaded beyond the yield point. This explanation assumes that damage would be localised to the area around the fracture. Therefore, the material properties of a coupon taken a certain distance away from the fracture would not be significantly influenced by a damage gradient. Given that yield stress and yield strain were significantly different between the fractured and control ribs, some damage had to be present in the coupons from the fractured ribs to cause a change in material properties. This lends support to the first explanation. However, the disparity between the current study and the literature on whether the modulus is significantly affected by post-yield loading may indicate that the coupons from the current study were taken too far from the fracture to affect the modulus. Therefore, it is likely that the results were influenced by the coupons being taken both from a narrow range of locations as well as too far from the fracture for some material properties to be affected.

The main limitations of this study were due to subject size and sample demographics. A larger sample size would provide more statistical power to overcome inter-subject variability. Additionally, the design of this study was based upon on the findings of previous studies that rib material properties do not vary significantly within a subject [11][12]. However, intra-subject variability can still influence the results if only one sample is taken from each subject for each test condition, as was done in this study. Testing multiple samples would reduce the influence of intra-subject variability on material properties and results, but is not always feasible when a limited amount of bone is available. Finally, the subjects included in this study spanned a wide range of ages, but only one subject was less than 50 years old. [5] reported differences in damage accumulation between cortical bone samples from young (26 ± 5 years) and elderly (72 ± 6 years) subjects that were loaded in tension to failure. Therefore, it is possible that the material properties of younger and older subjects could be affected differently by post-yield loading.

Future work could be performed to better evaluate the influence of the distance between the fracture and coupon on the material properties. For example, several coupons could be taken from each rib at set distances from the fracture, which would better encompass the gradient of damage when evaluating the effect of fracture distance on material properties. However, there are several factors that would complicate or limit such an analysis. First, only a limited amount of continuous cortical bone is available for material testing on each rib after fracture. Irregularities in the geometry of the rib and the length of the coupons further decrease both the number of coupons that could be fabricated from each rib and the possible locations of these coupons along the rib. Furthermore, some ribs fracture in two places, greatly decreasing the amount of continuous bone available for coupon fabrication. Therefore, assessing the material properties at greater distances from the fracture, e.g., 50% of rib length, may not be possible for a majority of subjects. Second, the fracture locations are not always consistent between ribs, leaving a different amount of bone remaining on each end of the fracture for each subject. This would result in either a different number of coupons at each set distance across all subjects, which is difficult to evaluate using a robust statistical analysis, or a narrow range of lengths over which a coupon is available from each subject. As observed in the current study, evaluating the effect of the distance between the fracture and coupon on material properties over a narrow range of distances may not encompass enough of the damage gradient to yield statistically significant results.

The results of this study have several implications on finite element modelling. First, subject-specific structural and material properties are desirable for developing and validating finite element models of subject-specific PMHS tests. It is often impossible to obtain cortical bone material properties after a structural test due to the destructive nature of the tests. Specifically, there may not be enough intact cortical bone remaining post-test to obtain a coupon for material testing. Additionally, the material properties may be altered as a result of loading the bone beyond the yield point. However, the results of the current study indicate that it may be possible to estimate some pre-failure material properties from ribs that underwent destructive whole rib bending tests. Having the ability to obtain structural and material properties from the same bone would increase the amount of data available for the development and validation of finite element models. Additionally, the amount of donor material needed to obtain material and structural properties would be decreased if these properties could be obtained from the same bone, potentially conserving donor material for other studies. Finally, post-yield and post-failure material properties are of interest for finite element model validation of loading scenarios that involve multiple distinct loading events, e.g., belt loading followed by steering hub loading.

V. CONCLUSIONS

The current study found that the material response of cortical bone obtained from previously fractured ribs was qualitatively and quantitatively different from the cortical bone obtained from the control ribs. Yielding occurred earlier and more gradually in the stress-strain curve for the fractured ribs. Consequently, the fractured ribs had significantly lower yield stresses and yield strains compared to the control ribs. However, the modulus, failure stress, failure strain, and strain energy density were not significantly different between the fractured and control ribs. Therefore, it may be possible to estimate the pre-failure modulus, failure strain, failure stress, and strain energy density of the cortical bone from a rib that was tested in similar conditions as the whole rib bending tests, provided the tested coupon is sufficiently far from the location of fracture. This finding can facilitate the derivation of subject-specific material and structural properties for use in finite element models. However, due to the limited sample size and variance within an individual, additional testing is needed to more thoroughly evaluate how injurious loading affects material properties along the length of a rib.

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