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CIB Report Number 2006-100

Failure Properties of the Human Thoracolumbar Spine Applicable to Far-Side Automotive Impacts

PREPARED FOR

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June 23, 2006

1. Introduction

The human spine is a complex load bearing structure that has been the focus of numerous biomechanical studies. These studies provide valuable data that can be used to characterize both vertebral bodies and intervertebral discs, validate computational models, and provide insight on the mechanisms that result in spinal injuries. The literature covers a range of both nondestructive and destructive testing of the entire spinal column, C1-L5. However, this document will focus primarily on the destructive, or failure, testing of the thoracolumbar spine, T1-L5. The literature summarized in this document provides invaluable failure data that can be used in the development of thoracolumbar spine injury tolerances for far-side automotive impacts.

2. Summary of Literature

The research aimed at determining the failure properties of the thoracolumbar spine can be broken up into three main areas: isolated vertebral bodies; functional spinal units; and multiple vertebral body spinal segments. The literature can then be further divided into different experiment types within each of these areas: compression, tension, shear, and bending (Figure 1). The remainder of this document summarizes the literature concerning the different experiment types within each of the three main areas of failure testing.

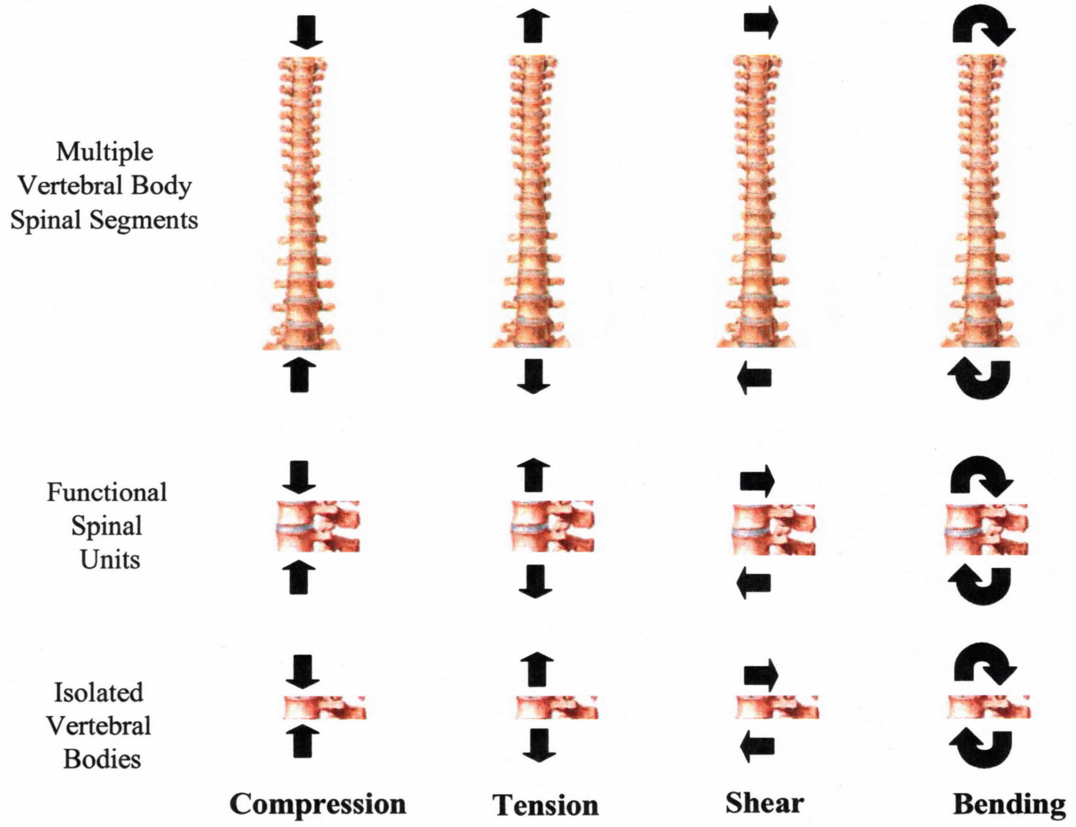

Figure 1: Various types of spinal column failure property testing.

2.1. Isolated Vertebral Bodies

Numerous researchers have investigated the failure properties of isolated vertebral bodies, which is a primary support structure in the spinal column. An isolated vertebral body is one that has been removed from the spinal column and cleaned of any soft tissue, ligaments, and intervertebral discs. The primary method of testing isolated vertebral bodies has been axial compression. Failure has been described by most researchers as crushing of the vertebral body generally accompanied by an audible crack and leaking of marrow from the body. Messerer (1880) reported the average compressive failure load for the upper thoracic vertebral bodies, middle thoracic vertebral bodies, lower thoracic vertebral bodies, and lumbar vertebral bodies to be 1957 N, 2275 N, 3560 N, and 3914 N respectively. Sonoda (1962) reported the average compressive failure load for the upper thoracic vertebral bodies, middle thoracic vertebral bodies, lower thoracic vertebral bodies, and lumbar vertebral bodies of all cadavers (20-79 yrs) to be 3028 N, 3388 N, 4493 N, and 4954 N respectively. Sonoda (1962) also reported the compressive average failure load for the upper thoracic vertebral bodies, middle thoracic vertebral bodies, lower thoracic vertebral bodies, and lumbar vertebral bodies of just the younger cadavers (20-39 yrs) to be 3630 N, 4228 N, 6317 N, and 7161 N respectively. Neither Messerer (1880) nor Sonoda (1962) reported the loading rate at which the vertebral bodies were tested. Hanssen (1979) reported the compressive average failure load for the lumbar vertebral bodies of all cadavers (31-79 yrs) and young male cadavers (31-45 yrs) to be 3834 N and 6701 N respectively. Hutton (1979) reported the compressive average failure load for the lumbar vertebral bodies of all cadavers (17-65 yrs) tested at 0.1 mm/s and 5mm/s to be 5347 N and 7215 N. Hutton (1979) reported the compressive average failure load for the lumbar vertebral bodies of just the young cadavers (17-50 yrs) tested at 0.1 mm/s and 5mm/s to be 6066 N and 7861 N respectively. Therefore, Hutton (1979) showed that the failure load of thoracic vertebral bodies in axial compression is both rate and age dependent. Pintar (1986) tested vertebral bodies at a loading rate of 2.54 mm/s, and reported the average compressive failure load for T1-T6, T7-T12, and L1-L5 to be 2642 N, 3264 N, and 4590 N respectively. Kazarian (1977) tested thoracic vertebral bodies from young cadavers (26-38 yrs) in axial compression while controlling for vertebral body level, at three different loading rates: 0.0889 mm/s, 8.89 mm/s, and 889 mm/s. Kazarian (1977) reported the average failure loads for each loading rate to be 3896 N, 5374 N, and 8691 N respectively. Like previous researchers, Kazarian (1977) also reported that for each loading rate the average failure load increased from superior to inferior vertebral bodies.

2.2. Functional Spinal Units

Functional spinal units (FSU), defined as an intervertebral disc and all or part of the two adjacent vertebral bodies, have been the most extensively studied of the three areas of spinal failure property research. The most desirable failure property of FSUs, with respect to far-side automotive impacts, is lateral bending. Unfortunately, there have been no studies that have investigated the failure properties of FSUs in lateral bending. Therefore, this section only summarizes the key studies that have investigated the failure properties of FSUs in compression, tension, and shear.

Similar to isolated vertebral bodies, the primary method of testing FSUs has been axial compression. Brown (1957) reported the compressive average failure load of lumbar FSUs to be 5204 N. Perry (1957) reported the average compressive failure load of lumbar FSUs due to static loading of all cadavers (<40 to >60 yrs) and younger cadavers (<40 yrs) to be 5284 N and 7636 N respectively. Sonoda (1962) reported the average compressive failure load for the upper thorax, middle thorax, and lumbar FSUs to be 4415 N, 11282 N, and 14715 N respectively. Neither Brown (1957) nor Sonoda (1962) reported the loading rate used for testing. Yoganandan (1989) tested thoracolumbar FSUs with both normal and degenerated discs at a loading rate of 2.54 mm/s and found the average compressive failure loads to be 11030 N and 5300 N, respectively. Duma (2006) tested lumbar FSUs at a loading rate of 1000 mm/s and found the average compressive failure load to be 12411 N. The primary modes of failure resulting from this type of testing have been reported to be fractures of the end-plate and crushing of the vertebral body. Injury to the intervertebral disc a result of a single axial compression loading event, static or dynamic, has been found to be rare.

Although axial compression has been the primary method of testing, a limited number of researchers have investigated the failure properties of FSUs in pure tension. Sonoda (1962) reported the average tensile failure loads of the upper thorax, lower thorax, and lumbar regions to be 1156 N, 2391 N, and 3185 N respectively. Pintar (1986) tested FSUs at a loading rate of 10 mm/s, and reported the average tensile failure loads of the thoracic and lumbar regions to be 597 N and 1254 N, respectively. Unfortunately, it is difficult to determine the reason for the differences in the results reported by the two researchers because Sonoda (1962) did not report the loading rate at which the specimens were tested. Sonoda (1962) and Pintar (1986) both reported that primarily failure occurred either fully or partially at the endplate junction.

There has only been one researcher to the author's knowledge that has investigated the failure properties of FSUs in direct shear. Sundararajan (2005) tested FSUs from the lumbar spine with a preload of 1000 N at two shear loading rates, and reported the average shear failure load at 0.5 mm/s and 500 mm/s to be 1850 N and 2616 N respectively. Sundararajan (2005) reported the primary failure mode at quasi-static shear forces to be disc-endplate separation accompanied by failure of posterior bony structures and the facet joint capsule. Sundararajan (2005) reported the failure mode at dynamic shear forces to be disc injuries and failure of bony fractures and the facet capsule separation. Disc injuries were not described in detail for the dynamic tests.

2.3. Multiple Vertebral Body Spinal segments

The literature on the failure properties of multiple vertebral body spinal segments of the thoracolumbar spine is the most limited of the three main areas of spinal failure property research. However, there are a few studies that provide valuable insight into the failure properties and failure mechanisms of multiple thoracolumbar vertebral body spinal segments (Yoganandan, 1988; Myklebust, 1989; Duma, 2006). The testing type, failure properties, and failure modes of these studies have been summarized (Table 1).

Similar to FSU testing, there have been no studies that have investigated the failure properties of multiple thoracolumbar vertebral body spinal segments in lateral bending. However, Demetropoulos (1988) conducted sub-failure stiffness testing on 10 multiple lumbar vertebral body spinal segments, T12-L5, in compression, tension, flexion, extension, lateral bending, anterior shear, posterior shear, and lateral shear. The average maximum sub failure moment in lateral bending was reported to be 113 Nm. The average maximum sub failure load in anterior shear, posterior shear, and lateral shear was reported to be 830 N, 1760 N, and 150 N respectively.

Table 1: Failure properties of multiple vertebral body spinal segments.

Reference	**Spinal Level**	**Experiment**	**Loading Rate**	**Average Failure Load (N)**	**Average Failure Moment (N-m)**	**Failure Mode**
Yoganandan (1988)	T3-L5 (9) T2-L5 (4) T4-L5 (1) C2-L5 (2) T6-L5 (2)	compression-flexion	2.5 mm/s	2344 1192 444 679 5418	177 99 289 84 284	Spinal column fracture due to wedging (T10-L2)
	T2-L3 T3-L2 T8-L3	Three-point Bending (flexion)	2.5 mm/s	1681 2170 1432	201 326 129	Center of spine at point of maximum flexural moment
	T12-L5 T4-L4 T10-L2	Four-point Bending (flexion)	2.5 mm/s	4893 1712 1544	245 86 77	Center of spine at point of pure flexural moment and no shear
Myklebust (1989)	T2-T9 T10-L1 (n=14)	compression (neck flexed)	ranged from 10-1200 mm/s	1223 2680	N/R	Wedge fractures from T9-L1
	intact cadaver (n=4)	Compressive load applied to T1	10 mm/s	1788	N/R	wedge /compression fractures at thoracolumbar junction
Duma (2006)	T12-L5 (n=2)	Axial compression (anatomically oriented in seated position)	1000 mm/s	5460	201	wedge /compression fractures of T12
FAA (1996)	Compressive lumbar load limit during restraint system testing POD in line with spinal column		dynamic	6672	-	N/A

3. Suggested Thoracolumbar Allowable Limits

While all is not know with respect to the failure properties of the spine and there are many methods of testing, the following provides a first order approximation for thoracolumbar injury criteria. Allowable limits for the thoracolumbar spine were developed based on the failure properties reported from all three of the areas of spinal failure property research, (Table 2). The suggested criteria was determined by averaging the failure data, rounded to the nearest hundredth, of predominantly young male cadavers tested at static to semi dynamic rates. Therefore, the suggested criteria can be used for testing with the 50th Percentile Hybrid III dummy. If there was insufficient data for certain regions in a specific testing mode, then the criteria was scaled based on the averages reported for compression testing because it was the most complete data set. Allowable limits are suggested for the upper thorax, middle thorax, and lumbar regions because these regions correspond to the locations of spinal load cells in the 50th Percentile Hybrid III dummy.

Table 2: Suggested allowable limits for the thoracolumbar spine.

	Pure Compression (N)	**Pure Tension (N)**	**Pure Shear (N)**	**Combined Compression/ Moment**
Upper Thoracic	3100	800	900	100 N-m (@ 1400 N)
Middle Thoracic	4500	1600	1300	146 N-m (@ 2000 N)
Lumbar	6200	2200	1800	200 N-m (@ 2430 N)

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