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# Research, Development, Testing and Evaluation of Vehicle Anti-Ram Barriers: Tests of 100 kN (22 kip) BRUBelt Specimens

Bernard A. Frankl

*University of Nebraska-Lincoln*, [bafrankl83@gmail.com](mailto:bafrankl83@gmail.com)

Daniel Linzell

*University of Nebraska-Lincoln*, [dlinzell@unl.edu](mailto:dlinzell@unl.edu)

Peter Hilsabeck

*University of Nebraska-Lincoln*, [philsabeck2@unl.edu](mailto:philsabeck2@unl.edu)

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# **RESEARCH, DEVELOPMENT, TESTING AND EVALUATION OF VEHICLE ANTI-RAM BARRIERS**

## **Tests of 100 kN (22 kip) BRUBelt Specimens**

### Submitted by

Bernard A. Frankl, P.E.  
Graduate Research Assistant

Daniel Linzell, Ph.D., P.E.  
Voelte-Keegan Professor and Chair

Peter Hilsabeck  
Laboratory Technician

### **DEPARTMENT OF CIVIL ENGINEERING**

University of Nebraska-Lincoln  
844 N. 16th St., N104 SLNK  
P.O. Box 886105  
Lincoln, NE 68588-6105  
(402) 472-2371

### Submitted to

### **THE PENNSYLVANIA STATE UNIVERSITY**

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## **ABSTRACT**

A series of tests were performed at the University of Nebraska-Lincoln on 100 kN (22 kip) BRUbelt, produced by the Brugg Group<sup>1</sup>. As stated on the BRUbelt website, this product consists of a series of small diameter steel cords encased in a viscoelastic material consisting of a surface that is in contact with the cords and a non-abrasive outer layer. This outer layer is predominantly used to provide corrosion protection. BRUbelt was identified as a possible candidate for implementation into various protective barrier systems being studied by the Pennsylvania State University in affiliation with the United States Department of State. The University of Nebraska-Lincoln was contracted by Penn State to ascertain mechanical properties of 100 kN (22 kip) BRUbelt with and without connecting elements in place under static and dynamic loads. These tests were intended to ascertain capacities under demands that mimicked possible conditions encountered in various protective barrier systems in the field and to provide constitutive property data to the Pennsylvania State University for possible implementation into computational models used to ascertain protective barrier system performance. Tests included static tension tests of BRUbelt specimens with and without connecting elements, static bending BRUbelt specimen tests and, based on findings during the test program, dynamic tension tests of BRUbelt specimens with and without connecting elements. Static tension tests showed consistent material properties, with the material largely failing in a brittle fashion and with a mean static tensile capacity of 112 kN (25 kips), an ultimate strength of 2316 MPa (336 ksi) and an elastic modulus of 18047 MPa (2618 ksi). BRUbelt with and without connecting elements displayed identical behavior under static loads, which indicated that the examined connecting elements did not adversely degrade specimen strength or stiffness. Static out-of-plane tests showed minimal flexural stiffness but did show that local bearing effects can affect the strength

under tight radius bearing points. Dynamic testing exhibited similar properties to the specimens under static loads and showed that there were minimal, if any, rate effects on behavior. Results with and without connecting elements displayed statistical identical behavior showing the connecting element does not affect the strength or stiffness.

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# 1. INTRODUCTION

The University of Nebraska-Lincoln was contracted by the Pennsylvania State University to ascertain the mechanical properties of BRUBelt with and without connecting elements in place under static and dynamic loads. These tests were intended to ascertain capacities under demands that mimicked possible conditions encountered in various protective barrier systems in the field and to provide constitutive property data to the Pennsylvania State University for possible implementation into computational models used to ascertain protective barrier system performance.

Brugg Group produces a line of belts offering appreciable tensile capacity within a relatively small cross section, termed BRUBelt Systems<sup>1</sup>. This system is used as an alternative to other tensile members including machine and plant manufacturer, monitoring systems, renewable energy, supplier to electricity supply companies, and lifting equipment<sup>1</sup>. The product line consists of a series of small diameter steel cords encased in a viscoelastic material consisting of a surface that is in contact with the cords and a non-abrasive outer layer. It includes products of varying tensile capacity, with the highest commonly available product having a capacity of 100 kN (22 kip).

The use of BRUBelt within protective barrier systems was explored as an alternative to traditional, epoxy-coated cable (strand), primarily due to anticipated enhanced corrosion resistance.



## 2. TEST SETUP AND RESULTS

### 2.1. Parametric Study

Static and dynamic tests of BRUbelt under tension and out-of-plane bending were completed with and without connecting elements. To help develop the matrix of tests needed to adequately characterize BRUBelt behavior, specimens with and without connecting elements under conditions that were deemed representative of actual static and dynamic demands were considered and a two-way treatment design was applied to ensure that all combinations and comparisons were adequately represented<sup>2</sup>. Two-way treatment design consists of a set of “treatments,” which represent the loading type tested over multiple levels. Treatments were loads subjected to each specimen and the rates that they were applied and consisted of static tension, static bending, dynamic tension and dynamic bending. “Levels” for each treatment were either without or with connecting elements. The two-way treatment design resulted in eight combinations as shown in Table 1. Each combination was subject to three iterations to develop an adequate statistical power resulting in 24 tests.

Table 1: Two-way treatment design test matrix

	Connecting Elements	
	With	Without
Static Tension	3 tests	3 tests
Static Bending	3 tests	3 tests
Dynamic Tension	3 tests	3 tests
Dynamic Bending	3 tests	3 tests

As will be shown in Table 5 through Table 13, results from static tension tests indicated connecting elements and out-of-plane bending did not appreciably change BRUBelt performance when compared to specimens that were loaded in tension without connecting elements and, as a

result, allowed for elimination of static out-of-plane bending tests with connecting elements as well as dynamic out-of-plane bending tests with and without connecting elements. This permitted ignoring the tests shown in italics in Table 1 as the testing program progressed.

## 2.2. Specimen Preparation

Specimens consisted of 152 mm (30.00 in) sections of BRUbelt inserted into wedges provided by Brugg Group as shown in Figure 1. This arrangement provided a clear distance of 152 mm (6.00 in) between wedges. BRUbelt specimens were cut to necessary lengths per Brugg Group field directives utilizing a portable band saw. For specimens with connecting elements, single connecting elements (Brugg wedges) were utilized during tests due to length restrictions in the universal testing frame used to complete static tensile tests (see Figure 2 and Figure 3). This single wedge was connected to a BRUbelt specimen via a shear pin as shown in Figure 4. All BRUbelt specimens were seated into the Brugg Group wedges by preloading to 4 kN (1 kip) in the universal testing frame.

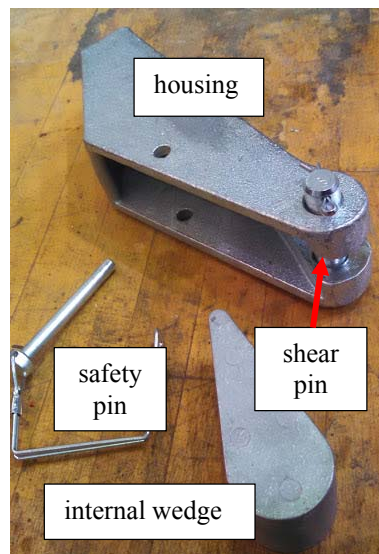


Figure 1: Brugg Group wedge

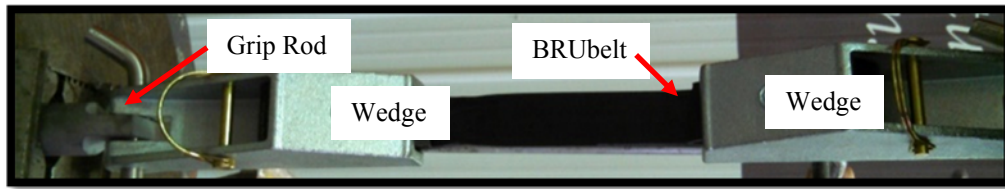


Figure 2: BRUbelt specimen

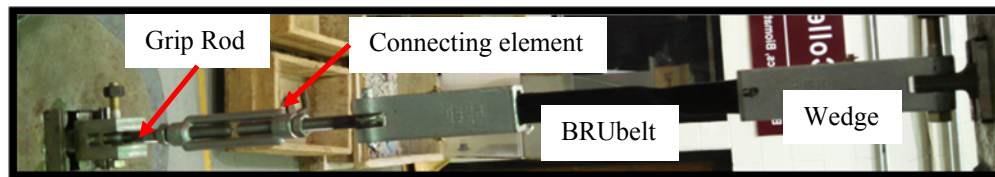


Figure 3: BRUbelt specimen with connecting element

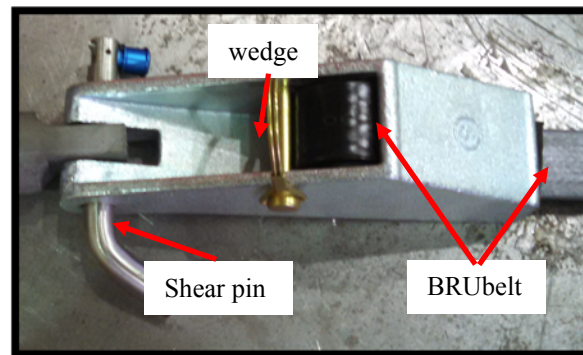


Figure 4: Brugg Group wedges with specimen

### 2.3. Test Preparation

Specimen properties needed to be determined before testing parameters could be selected. The average cord diameter of 0.46 mm (0.02 in) and a total average cross sectional area of 48.3 mm<sup>2</sup> (0.075 in<sup>2</sup>) was measured utilizing guidelines given in ASTM A1007-07<sup>3</sup>. Initial length measurements for strain calculations were determined by measuring the length between the Brugg Group wedges and adding half the perimeter of the internal wedge resulting in a gage length as shown in Figure 5. Half of the internal wedge perimeter was included in the gage length based on visual observation of seating distances during BRUbelt specimen preloading.

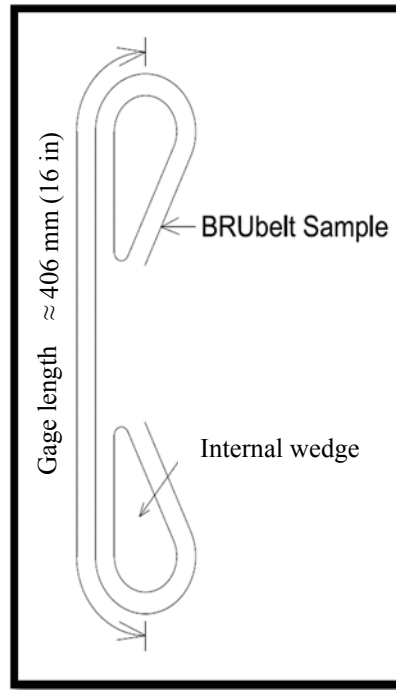


Figure 5: Gage length

The average specimen cross sectional area was used to determine the estimated BRUbelt specimen strength of 2072 MPa (301 ksi) which was used in turn to determine the specimen loading rate of 22 kN/min (5 kip/min) based on ASTM A931-08<sup>4</sup> and ASTM E8-13a<sup>5</sup>. Dynamic testing rates were determined by examining static strain energy results, shown in Table 5, Table 6, Table 9 and Table 13.

## 2.4. Static Tension

### 2.4.1. Test Setup

Observed tension failure never occurred in uniform fashion. To ensure that consistent data was collected from the static tension test, four BRUbelt specimen without connecting elements were examined. The number of BRUbelt static tension test specimens with connecting

elements that were tested was unchanged from that shown in the Table 1. A list of all static tension tests with specimen length and measured gage length detailed is provided in Table 2 and Table 3 and an updated test matrix is seen in Table 4.

Table 2: Static tension tests without connecting elements

BRUbelt Specimens	Specimen Length mm (in)	Gage Length mm (in)
TS1	600 (26.00)	394 (15.50 )
TS2	762 (30.00)	397 (15.63)
TS3	762 (30.00)	442 (17.19)
TS4	762 (30.00)	457 (18.00)

Table 3: Static tension tests with connecting elements

BRUbelt Specimens	Specimen Length mm (in)	Gage Length mm (in)
TSC1	762 (30.00)	429 (16.63)
TSC2	762 (30.00)	426 (16.75)
TSC3	762 (30.00)	416 (16.38)

Table 4: Two-way treatment design test matrix, revision 1

	Connecting Elements	
	With	Without
Static Tension	3 tests	4 tests
Static Bending	3 tests	3 tests
Dynamic Tension	3 tests	3 tests
Dynamic Bending	3 tests	3 tests

Static tension tests were performed in a Southwark Emery SN 64305 universal testing frame that has a tensile capacity of 979 kN (220 kip), located in the University of Nebraska-Lincoln Structural Testing Laboratory and shown in Figure 6. Tests were controlled using an Instron M47-16604-EN controller. The movable head is guided using screw jacks that are

hydraulically controlled using the Instron controller. Load was measured utilizing a load cell built into the universal testing frame and displacements were measured utilizing a linear variable differential transformer (LVDT) housed within the universal testing frame. Specimens were affixed to the universal testing frame machine using the grip rods detailed in Figure 2 and Figure 3 in wedges in the movable stationary heads.

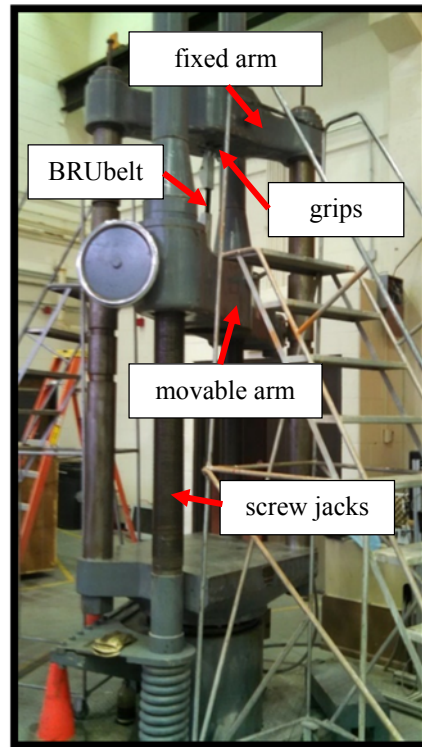


Figure 6: Southwark Emery SN 64305 universal testing frame

#### 2.4.2. Experimental Results

BRUbelt static tension tests demonstrated largely a brittle failure mechanism that was precipitated by failure of individual wires in the steel cables followed by rapid tensile failure of remaining cables in the specimens. This was then followed by subsequent necking of the non-abrasive outer coating at the fracture location after failure of the steel cords. This type of failure was observed in specimens with and without connecting elements. Brittle tensile failure was observed to occur adjacent to Brugg Group wedges for all tests as shown in Figure 7.

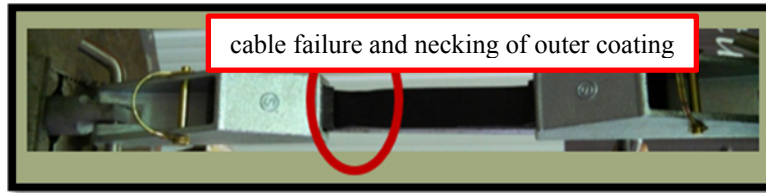


Figure 7: Static tension failure

Measured loads and displacements for all tests were converted to stress and strain utilizing measured geometric property data reported in Table 2 and Table 3. Subsequent stress-strain plots were developed to identify material performance data in tension, which could include, if applicable, the proportional limit, yield and ultimate stresses and the modulus of elasticity. Strain energies for each test were determined by integrating the stress-strain curve.

Review of stress-strain curves for the static tension without connectors showed linear elastic behavior preceding the previously discussed brittle failure at a total elongation up to 65 mm (2.50 in) over the average specimen length of 400 mm (15.75 in), corresponding to a failure strain of 0.15 mm/mm (in/in). Average axial load at failure for the static tension tests without connectors was 112 kN (25 kip), corresponding to a total average axial stress of 2316 MPa (336 ksi). Stress-strain curves showed an average modulus of elasticity of 18047 MPa (2618 ksi) and an average strain energy of 3.20 J (2.36 k-ft). Specimen stress-strain curves and a table summarizing results for the static tension tests without connectors can be seen in Figure 8 and Table 5.

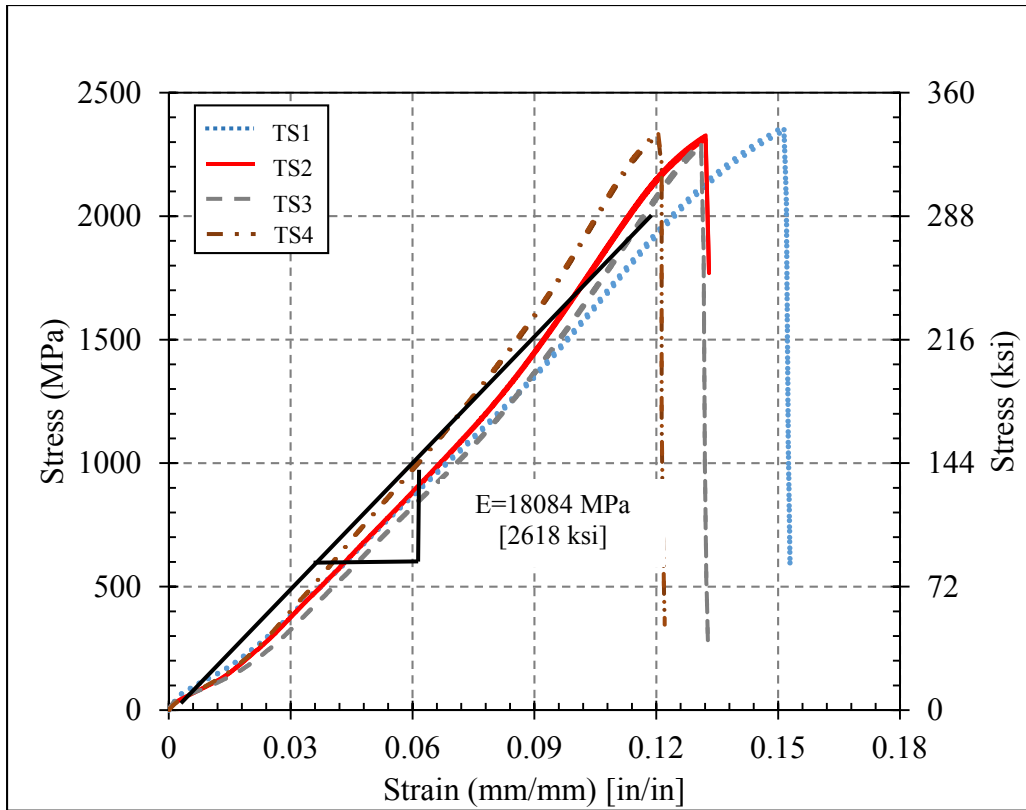


Figure 8: Static tension stress-strain curves, without connectors

Table 5: Static tension results, without connectors

BRUbelt Specimen	$P_{\max}$ kN (kip)	$\sigma_{\max}$ MPa (ksi)	E MPa (ksi)	Strain Energy J (k-ft)
TS1	113 (26)	2346 (340)	16299 (2364)	3.42 (2.52)
TS2	112 (25)	2311 (335)	18147 (2632)	2.97 (2.19)
TS3	110 (25)	2281 (331)	18030 (2615)	3.28 (2.42)
TS4	112 (25)	2327 (338)	19712 (2859)	3.13 (2.31)
Average	112 (25)	2316 (336)	18047 (2618)	3.20 (2.36)
Std. Dev.	1.33 (0.30)	27.46 (3.98)	1395 (202)	0.19 (0.14)
C.O.V.	0.01	0.01	0.08	0.06



Review of stress-strain curves for the static tension with connectors showed linear elastic behavior preceding the previously discussed brittle failure at a total elongation up to 65 mm (2.50 in) over the average specimen length of 400 mm (15.75 in), corresponding to a failure strain of 0.15 mm/mm (in/in). Average axial load at failure for the static tension tests with connectors was 111 kN (25 kip), corresponding to a total average axial stress of 2309 MPa (335 ksi). Stress-strain curves showed an average modulus of elasticity of 19512 MPa (2830 ksi) and an average strain energy of 3.12 J (2.30 k-ft). Specimen stress-strain curves and a table summarizing the results for the static tension tests with connectors can be seen in Figure 9 and Table 6.

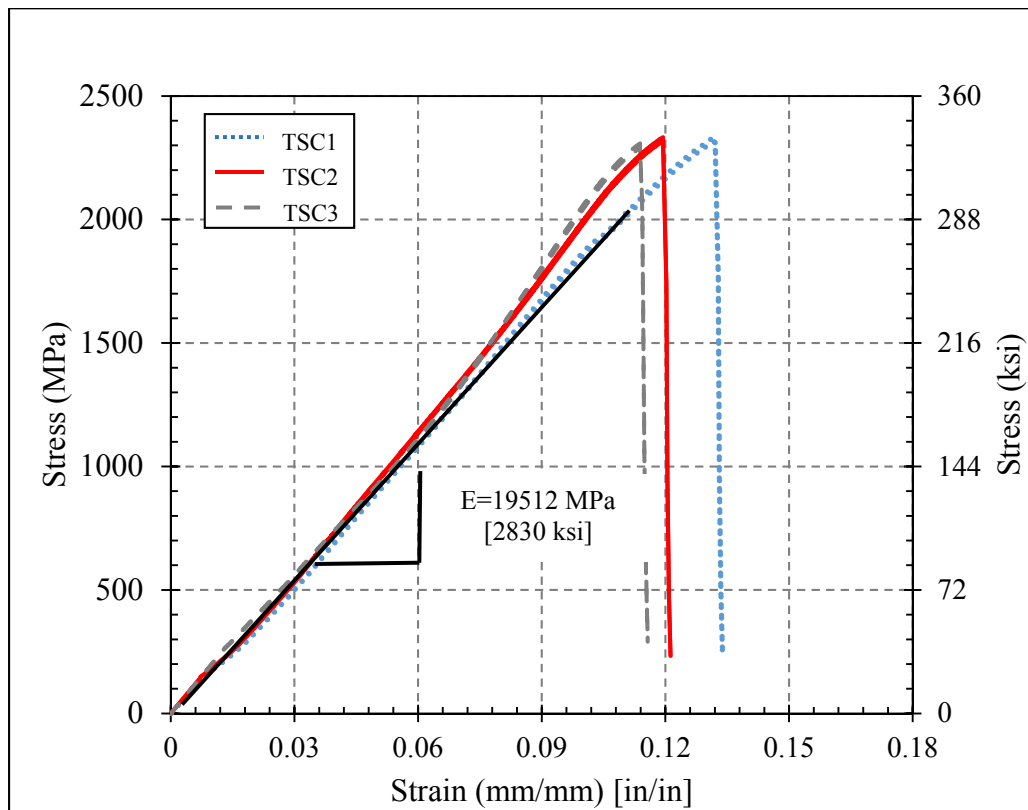


Figure 9: Static tension stress-strain curves, with connectors

Table 6: Static tension results, with connectors

BRUbelt Specimen	P <sub>max</sub> kN (kip)	σ <sub>max</sub> MPa (ksi)	E MPa (ksi)	Strain Energy J (k-ft)
TSC1	112 (25)	2317 (336)	18547 (2690)	3.51 (2.59)
TSC2	112 (25)	2317 (336)	19891 (2885)	2.98 (2.20)
TSC3	111 (25)	2292 (332)	20098 (2915)	2.86 (2.11)
Average	111 (25)	2309 (335)	19512 (2830)	3.12 (2.30)
Std. Dev.	0.69 (0.16)	14.40 (2.09)	842 (112)	0.35 (0.26)
C.O.V.	0.01	0.01	0.04	0.11

## 2.5. Static Bending

### 2.5.1. Test Setup

BRUbelt specimens were prepared utilizing the same method and lengths as detailed for static tension specimens in Table 7. Static bending tests that contained connecting elements were eliminated from the program due to static tension tests without connecting elements being the same as static tension tests with connecting elements, resulting in elimination of three tests from the test matrix as shown in Table 8.

Table 7: Static bending specimens

BRUbelt Specimen	Specimen Length mm (in)	Gage Length mm (in)
BS1	762 (30.00)	446 (17.56)
BS2	762 (30.00)	448 (17.63)
BS3	762 (30.00)	466 (18.38)

Table 8: Two-way treatment design test matrix, revision 2

	Connecting Elements	
	With	Without
Static Tension	3 tests	4 tests
Static Bending	0 tests	3 tests
Dynamic Tension	3 tests	3 tests
Dynamic Bending	3 tests	3 tests

Static bending tests were performed in a self-reacting frame located in the University of Nebraska-Lincoln Structural Testing Laboratory. Specimens were pinned to connecting plates affixed to the frame using the Brugg Group wedges. An Enerpac RRH-606 hydraulic ram was used to apply an out-of-plane point load at the center of the BRUbelt specimen and an Omega PX312 pressure cell was used to measure load applied to the BRUbelt specimens. An Enerpac LH-2506 analog load cell was placed between the hydraulic ram and a bearing plate to measure a redundant load for testing fixture verification. Displacements relative to each specimen's initial position were measured utilizing UniMeasure LX-PA-10-L1M string potentiometers where the specimen emerged from the wedges and at one-quarter and one-half the specimen length between the wedges. The load and measured out-of-plane displacement data were used to determine specimen axial loads and deformations as tests progressed. The static bending test configuration can be seen in Figure 10.

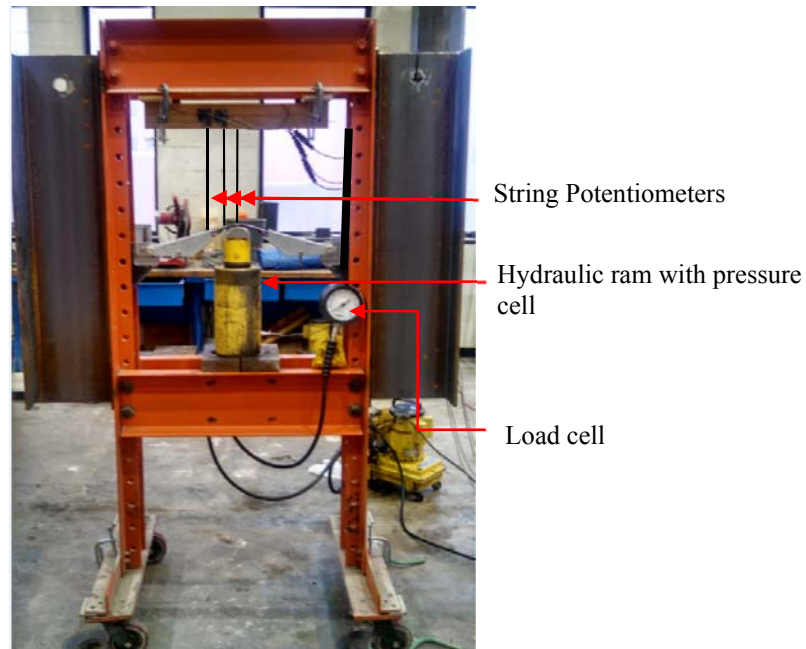


Figure 10: Static bending test configuration.

### 2.5.2. Experimental Results

Static bending tests demonstrated brittle failure as static tension tests. Failure occurred at the load point at mid-length of the specimens as shown in Figure 11. The bending specimens also were observed to “harp” during testing, as shown in Figure 12, behavior that was indicative of a lack of bending stiffness within the BRUbelt.



Figure 11: Static bending failure

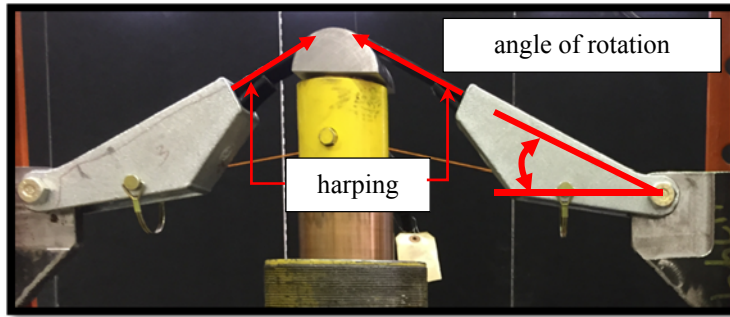


Figure 12: “Harping” of static bending specimens

Specimen stresses and strains were calculated as described in Section 2.4.2 once deformed specimen geometry axial loads and displacements were determined associated with each incremental loading step. Failure orientation showed severe angles of rotation (up to  $46^\circ$ ) over the 76 mm (3.00 in) bearing radius supplied by the loading platen, indicating the BRUbelt specimen exhibited primarily tensile behavior. Review of stress-strain curves for the static bending without connector specimens showed linear elastic behavior preceding the previously discussed brittle failure at a total elongation up to 57 mm (2.25 in) over the average specimen length of 450 mm (17.75 in), corresponding to a failure strain of 0.13 mm/mm (in/in). Average axial load at failure for the static tension tests was 90 kN (20 kip), corresponding to a total average axial stress of 1866 MPa (271 ksi). Stress-strain curves showed an average modulus of elasticity of 15520 MPa (2251 ksi) and an average strain energy of 2.58 J (1.90 k-ft). Specimen stress-strain curves and a table of summarizing results for the static bending tests can be seen in Figure 13 and Table 9.

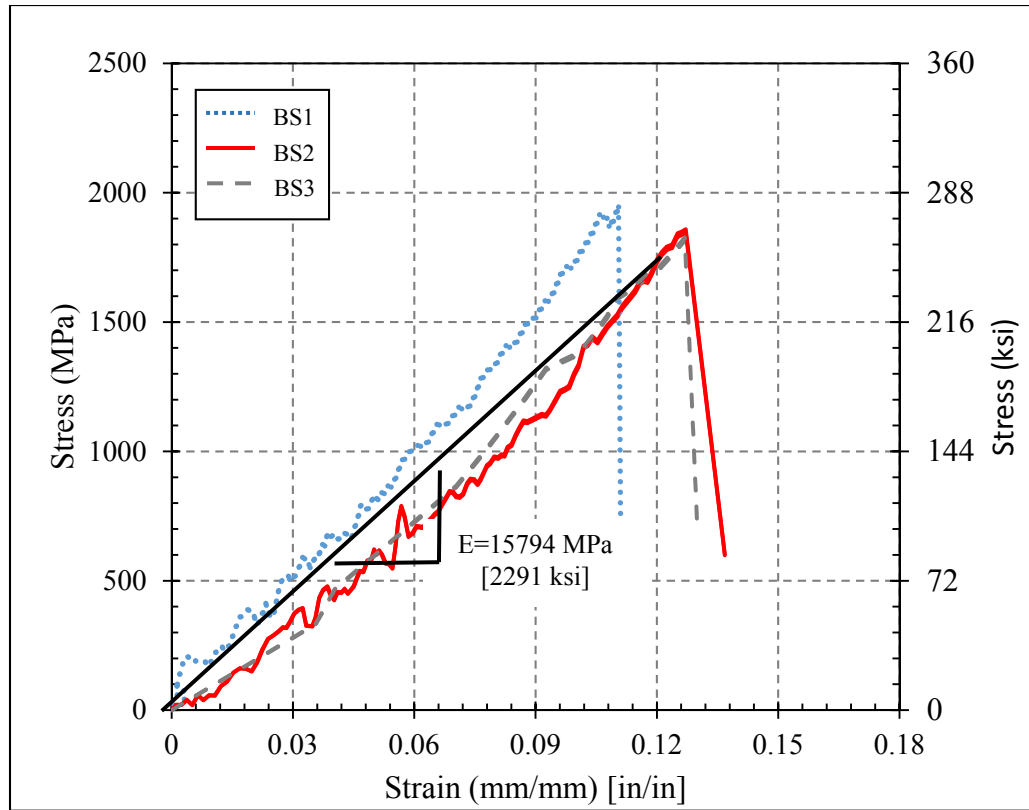


Figure 13: Static bending stress-strain curve

Table 9: Static bending results

BRUbelt Specimen	$P_{\max}$ kN (kip)	$\sigma_{\max}$ MPa (ksi)	E MPa (ksi)	Strain Energy J (k-ft)
BS1	94 (21)	1940 (281)	17554 (2546)	2.31 (1.71)
BS2	89 (20)	1845 (268)	14693 (2131)	2.82 (2.08)
BS3	88 (19)	1814 (263)	15134 (2195)	2.60 (1.92)
Average	90 (20)	1866 (271)	17554 (2291)	2.58 (1.90)
Std. Dev.	3.18 (0.71)	65.57 (9.51)	1540 (223)	0.26 (0.19)
C.O.V.	0.04	0.04	0.10	0.10

## 2.6. Dynamic Tension

### 2.6.1. Test Setup

The number of BRUBelt specimens tested dynamically changed from original quantities shown in the Table 1. Three dynamic tension tests of specimens without connecting elements were completed and four dynamic tension tests specimens with connecting elements were completed. Four tests of the specimens with connection elements were completed because BRUBelt specimen TDC2 did not experience failure. Dynamic bending tests were eliminated since static bending tests showed tensile behavior. All specimens were painted with a cross-hatched pattern as shown in Figure 14 so that high speed cameras could optically measure specimen displacements.

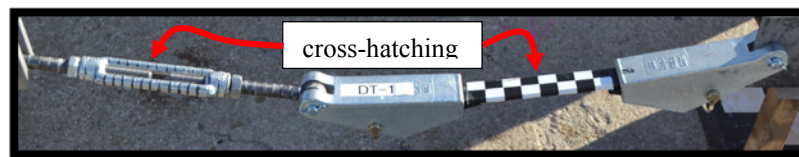


Figure 14: Dynamic tension specimen detailing cross-hatching

A list of all dynamic tension tests with the specimen length is shown in Table 10 and an updated test matrix is shown in Table 11.

Table 10: Dynamic tension specimens

BRUbelt Specimen	Specimen Length mm (in)
TDC1	76 (30.00)
TDC2	762 (30.00)
TDC3	762 (30.00)
TDC4	762 (30.00)
TD1	762 (30.00)
TD2	762 (30.00)
TD3	762 (30.00)

Table 11: Two-way treatment design test matrix, revision 3

	Connecting Elements	
	With	Without
Static Tension	3 tests	4 tests
Static Bending	0 tests	3 tests
Dynamic Tension	3 tests	4 tests
Dynamic Bending	0 tests	0 tests

Dynamic tests were performed at the Midwest Roadside Safety Facility (MwRSF), located in Airport Park in Lincoln, Nebraska, where controlled, vehicular, impact tests are commonly conducted. Dynamic forces were created by affixing BRUbelt specimens connected to a large, stationary, concrete mass and subjecting them to kinetic energy from a moving, four-wheeled frame of known mass (termed a “bogie”) pulled along a rail at a set speed using a cable system and tow-vehicle. A second stationary “bogie” was placed between the BRUbelt specimen and the moving bogie and used to dampen any energy while the moving bogie is accelerated to the desired impact velocity. Test specimens were connected to the concrete mass and the stationary “bogie” using pins and plates. Two load cells connected in series and between the



specimens and the concrete mass were used to measure applied loads. Forces placed onto the specimens and, subsequently, moving “bogie” speeds were selected so that behavior to failure could be monitored. The test configuration can be seen in Figure 15 through Figure 16.

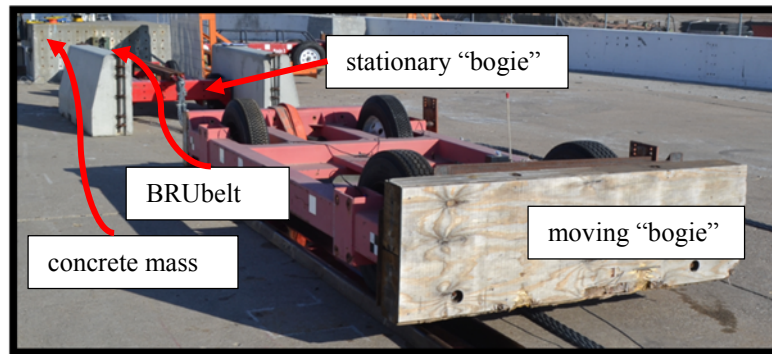


Figure 15: Dynamic test setup

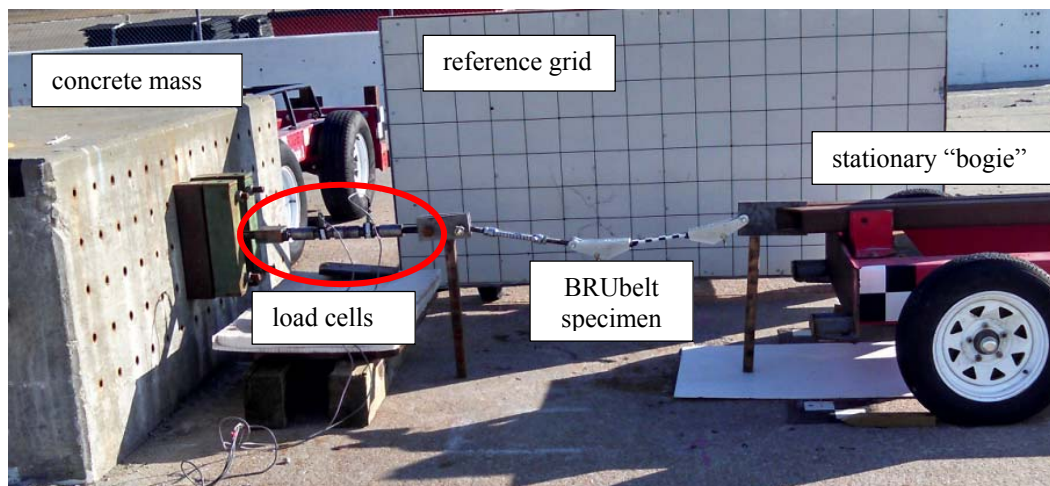


Figure 16: Concrete mass, specimen and load cells

As stated earlier, load cells measured applied tensile forces in the specimens while displacements were measured using an AOS S-VIT 1531 high speed camera placed orthogonal to and an AOS TRI-VIT high speed camera placed above with the BRUbelt specimens as shown in Figure 17 and Figure 18. As shown in Figure 14 and Figure 16, in addition to cross-hatching each specimen, a reference grid was placed in view of the orthogonal high speed camera to assist with specimen displacement measurements from the high-speed camera.



Figure 17: High speed camera locations

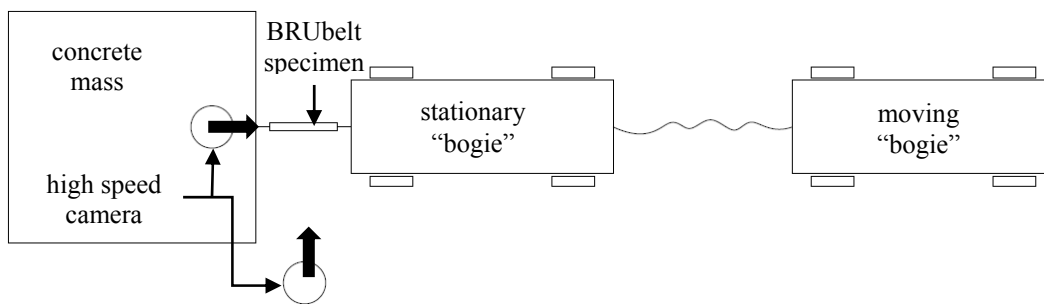


Figure 18: Dynamic tension setup plan

Necessary test speeds to produce specimen failure were determined by extracting calculated strain energies from the static tension tests and correlating those to an average kinetic energy imparted by the given mass of the “bogies.” Conservation of energy allowed for necessary “bogie” velocities to then be approximated. These calculated velocities were then arbitrarily increased by 50% and resulted in an approximate speed of 26 KPH (10 MPH) being needed to ensure consistent specimen failure.

## 2.6.2. Experimental Results

BRUbelt dynamic tension tests demonstrated largely a brittle failure mechanism followed by rapid tensile failure of remaining cables in the specimens. This was then followed by subsequent necking of the non-abrasive outer coating at the failure location after failure of the steel cords. Similar to static tension tests, brittle failure was observed to occur adjacent to Brugg

Group wedges for all tests as shown in Figure 19. Specimens TDC3, TDC4 and TDC4 experienced specimen failure inside the Brugg Group wedges, however, this failure did not significantly degrade their tensile strength when compared against specimens that failed outside the wedges. BRUbelt specimens with and without connecting elements were subject to an average velocity of 16 KPH (10 MPH) with the exception of specimen TD1 at 14 KPH (9 MPH) and TD2 at 12 KPH (8 MPH) which imparted enough kinetic energy to fracture all the specimens but BRUbelt TD2 as shown in Table 12.

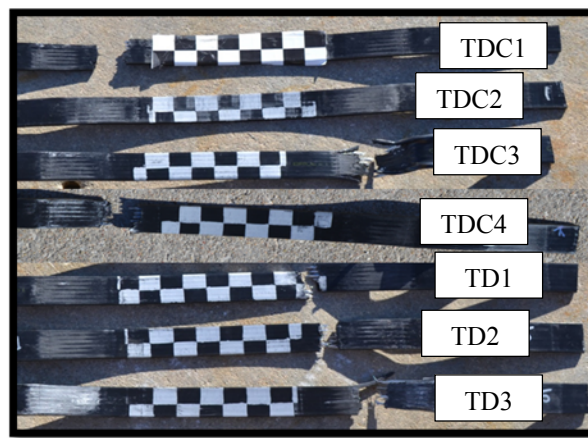


Figure 19: Dynamic tension specimens

Table 12: Dynamic tension test “bogie” velocities and imparted strain energies

BRUbelt Specimen	SPEED KPH (MPH)	STRAIN ENERGY J (k-ft)
TDC1	14 (9)	1.82 (1.34)
TDC2	12 (8)	1.04 (0.76)
TDC3	16 (10)	1.39 (1.03)
TDC4	16 (10)	2.96 (2.19)
TD1	15 (9)	1.60 (1.18)
TD2	16 (10)	1.79 (1.32)
TD3	16 (10)	1.59 (1.17)

Loads and displacements were converted to stresses and strains utilizing linear elastic, one-dimensional analysis involving the previously calculated cross sectional area with relative specimen elongation captured from high speed cameras and converted to displacements utilizing software from AOS Technologies. Subsequent stress-strain plots were developed to identify the material yielded stress, ultimate stress and modulus of elasticity. Strain energy of each test was determined by multiplying the gage length by the cross sectional area and the area under the stress-strain curve.

Review of stress-strain curves for the dynamic tension tests with and without connectors showed slightly bi-linear behavior preceding the previously discussed brittle failure at a total strain of 0.13 mm/mm (in/in). Average axial load at failure for the dynamic tension tests with and without connectors was 113 kN (26 kip), corresponding to a total average axial stress of 2348 MPa (335 ksi). Stress-strain curves showed an average modulus of elasticity of 21016 MPa (3048 ksi) and an average strain energy of 1.80 J (1.30 k-ft) and a failure strain energy between 1.14 J (0.84 k-ft) and 1.59 J (1.17 k-ft). Representative specimen stress-strain curves and a table summarizing results for the dynamic tension tests can be seen in Figure 20 and Table 13.

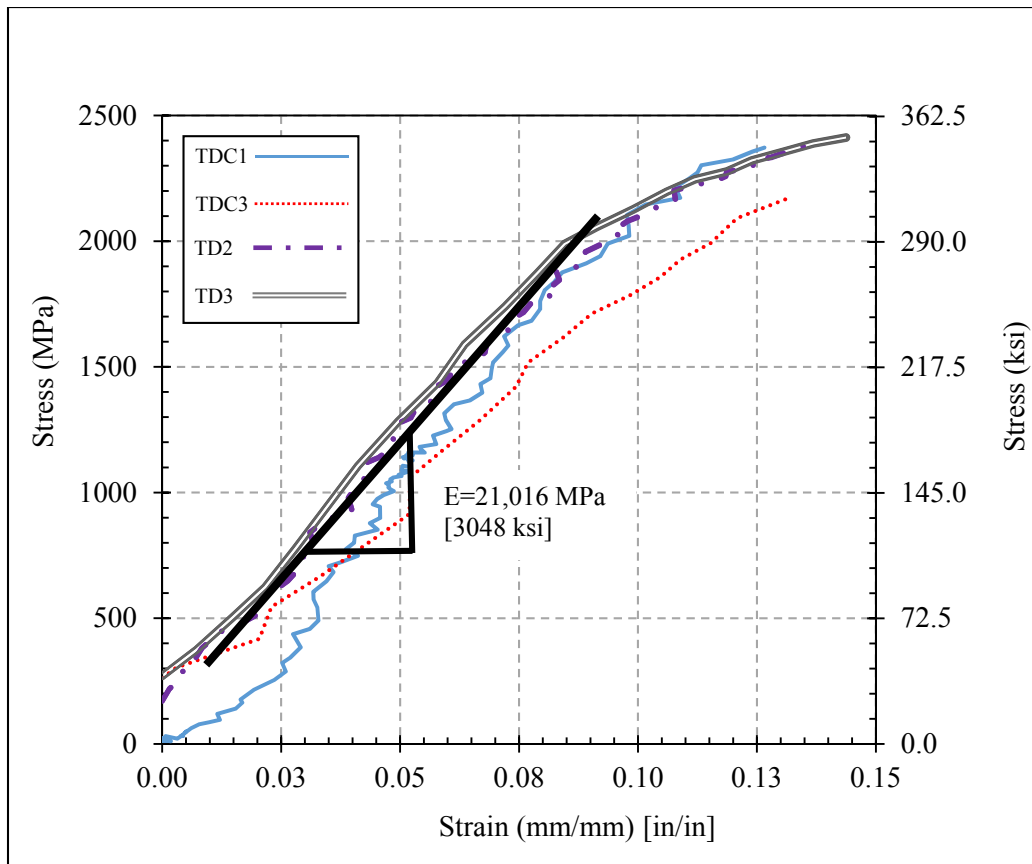


Figure 20: Dynamic tension stress-strain curve

Table 13: Dynamic tension results

BRUbelt Specimen	P <sub>max</sub> kN (kip)	$\sigma_{max}$ MPa (ksi)	E MPa (ksi)	Strain Energy J (k-ft)
TD1	117 (26)	2427 (352)	18484 (2681)	2.31 (1.71)
TD2	116 (26)	2401 (348)	21110 (3062)	2.82 (2.08)
TD3	117 (26)	2414 (350)	20191 (2928)	2.60 (1.92)
TDC1	114 (26)	2372 (344)	25555 (3706)	1.96 (1.44)
TDC2	107 (24)	2214 (321)	21594 (3132)	1.14 (0.84)
TDC3	105 (24)	2172 (315)	18484 (2681)	1.59 (1.17)
TDC4	118 (27)	2440 (354)	21693 (3146)	1.75 (1.29)
Average	113 (26)	2348 (341)	21016 (3048)	1.80 (1.30)
Std. Dev.	5.26 (1.18)	109.00 (15.81)	2412 (350)	0.36 (0.26)
C.O.V.	0.05	0.05	0.11	0.20

### 3. COMPARISONS

Test data suggests BRUbelt specimens can be analyzed utilizing Brugg Group<sup>1</sup> published material properties regardless of loading orientation and type (statically or dynamically) with and without connecting elements. Although out-of-plane, static, bending tests showed a slight reduction in capacity, the severe angle at which failure occurred (up to 46°) made it apparent that limited, if any flexural stiffness, was present in the specimens and they could be assumed to behave as tension-only elements. All BRUbelt specimens displayed brittle failure of the steel cords followed by necking of the outer coating, with the coating adding no appreciable strength

or ductility. Tensile behavior for all static tests was linear to failure irrespective of the BRUbelt loading orientation relative to the long axis of the belt. Tensile tests showed that the presence of the Brugg Group wedge connecting element did not degrade BRUbelt specimen performance whether the load was applied statically or dynamically. Dynamic effects did not appreciably affect BRUbelt specimen behavior.

#### **4. CONCLUSIONS**

A series of tests were performed at the University of Nebraska-Lincoln on 100 kN (22 kip) BRUbelt, produced by the Brugg Group<sup>1</sup>. Tests were performed under static tension loading with and without connecting elements and static bending at the University of Nebraska –Lincoln Structural Testing Laboratory and dynamic tension tests with and without connecting elements were performed at Midwest Roadside Safety Facility (MwRSF). Load and deformation data was collected and mechanical properties were ascertained and compared for each loading type. The following conclusions were ascertained:

- Static and dynamic tension tests, either with and without Brugg Group wedge connecting elements, demonstrated similar, linear behavior to brittle failure, with a mean tensile capacity of 112 kN (25 kip), a mean strength of 2316 MPa (336 ksi) and a mean modulus of elasticity of 18047 MPa (2618 ksi).
- Static bending tests demonstrated largely similar behavior as static and dynamic tensile tests with and without connecting elements with BRUbelt specimens subjected to out-of-plane loading having an observed capacity of 100 kN (22 kip) when specimens were subjected to a concentrated load applied using a steel loading head with a bend radius of 76 mm (3 in).

- BRUbelt specimens subjected to dynamic tensile loads had a failure strain energy between 1.14 J (0.84 k-ft) and 1.59 J (1.17 k-ft).
- BRUbelt specimens with and without Brugg Group wedge connectors can be effectively modelled as linear, tension only elements having a 100 kN (22 kip) ultimate capacity with a modulus of elasticity of 18000 MPa (2610 ksi) under static or dynamic loading.

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