CRITICAL EVALUATION OF BUNGEE-JUMPING ACCIDENT FAILURE ANALYSIS

MTRL 585
Case Study 1

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1.0 INTRODUCTION

In a journal article, author D.R.H. Jones summarized and analyzed the circumstances of a fatal bungee-jumping accident [1]. The approach taken by the failure analyst was critically evaluated to develop alternate methods of analyzing and portraying the findings.

2.0 FACTS AND EVENTS

2.1 Background

In 2002, breakage of bungee-jumping equipment resulted in the death of a jumper in the United Kingdom [1]. The author of the paper was requested to conduct a comprehensive analysis of the failure to determine the root cause. He was supplied the following items to aide in the investigation:

- The bungee jumping equipment involved in the incident;
- Similar equipment used in successful jumps;
- Videotapes, including one of the accident under investigation;
- Photographs taken at the scene of the accident;
- Supporting documentation.

The jumper weighed 132 kg and was 1.83 m tall, and was wearing long trousers made from a thin smooth fabric, short socks, and no shoes. He jumped from a cage that was suspended by a crane 53 m above the ground. The "inboard" end of the bungee rope was secured in the cage by a pair of snap hooks at a point 1.35 m above the level of the floor (i.e. 54.35 m above the ground). The bungee rope was 15.60 m in length and was comprised of three nominally equivalent cords that were taped together at regular intervals with insulating tape. Each cord had a braided sheath containing a large number of fine, parallel rubber filaments, and measured approximately 19 mm in diameter.

The "outboard" end of the rope was attached to the jumper by a pair of cuffs pulled tight around his lower legs. Each cuff was independently attached to the outboard end of the rope by a webbing strap. Suspended upside-down in this configuration, the soles of a jumper's feet would lie approximately 0.36 m below the end of the rope.

As a precautionary measure, the jumper's body harness was attached to the end of the rope via two endless slings. One endless sling, rated for 25 kN, was attached to the outboard end of the bungee rope. The other endless sling was cut to open the loop, with one end tied to the other endless loop and the other end tied to the jumper's body harness. Combined with the weakening effect of knotting the webbing, the breaking strength of this configuration would have been less than 12.5

kN. The total length of the webbing assembly was 2.13 m, of which 1.28 m was single. Measurements showed that there was approximately 0.6 m of slack in the webbing.

Once the jumper jumped from the cage, his body orientation moved from upright to inverted, and began to apply force to the rope. Under tension, his legs pulled out of the cuffs, thus transferring tension to the safety webbing. The safety webbing snapped at the knot near his feet, and he descended by free fall to the ground below.

2.2 Summary

Table 1 summarizes the key facts concerning the jump accident as presented in the investigator's report. The sequence of events is summarized as follows, in Table 2.

Table 1: Key facts regarding jump accident

Environment	Jump site	UK
Jumper	Weight	132 kg
	Height	1.83 m
	Center of gravity	Center of gravity ≈ 0.56*height [2] For this case, center of gravity = 1.03 m from feet
	Wearing	• 'Smooth' long trousers • Short socks • No shoes • Cuffs attached around 'lower legs' (≈ 0.3 m)
Bungee equipment / assembly	Cage	53 m from ground
	Rope	• Inboard end: secured by 'snap hooks' (54.35 m above ground) • Outboard end: attached to cuffs • 3 x rope cords 'apparently identical' • Each cord had a braided sheath (19mm OD) • Taped together at regular intervals • Distance between jumper's feet soles to outboard end of the rope (≈ 0.36m) • Unstretched length: L_o = 15.6 m • Limit of extension: L_{lim} = 16.0 m (100% strain) • Force at limit: F_{lim} = 3972 N (405 kg) • Breaking force: F_{break} > 3972 N
	Cuffs	2 cuffs which are independently attached to outboard end of rope with safety webbing
	Harness	Attached by safety webbing (single endless sling + single length of tape cut from an endless sling) to outboard end of rope

Bungee equipment / assembly	Safety webbing ('slings')	• Strength (without knot): $F_{web\text{-}nom} = 25$ kN • Strength (with knot): $F_{web\text{-}knot} < 12.5$ kN • Slack in webbing: $L_{slack} \approx 0.6$ m

Table 2: Sequence of events in jump accident

Initial	Jumper jumps from cage (53m above ground)	PE = mgh
Phase 1	Free-fall (jumper is in an inverted position)	PE lost ≈ KE_i
Phase 2	Jump rope reaches limit of extension (rope is in tension, jumper 'pulls-out' from cuffs)	SE_i < PE lost – KE gained
Phase 3	Initially slack, tension transfers to safety webbing (safety webbing snaps at the knot near the jumper's feet)	
Phase 4	Free-fall (jumper is fatally injured on impact)	(PE lost after release) + (KE at release) ≈ KE_i

**note: subscript "i" denotes instantaneous energy*

2.3 Schematic Diagram

Figure 1 shows a schematic of the bungee jump setup at the moment before tensioning of the bungee rope, showing the change in position of the center of gravity. This value is pertinent for calculation of potential energy lost and kinetic energy gained before the introduction of strain energy.

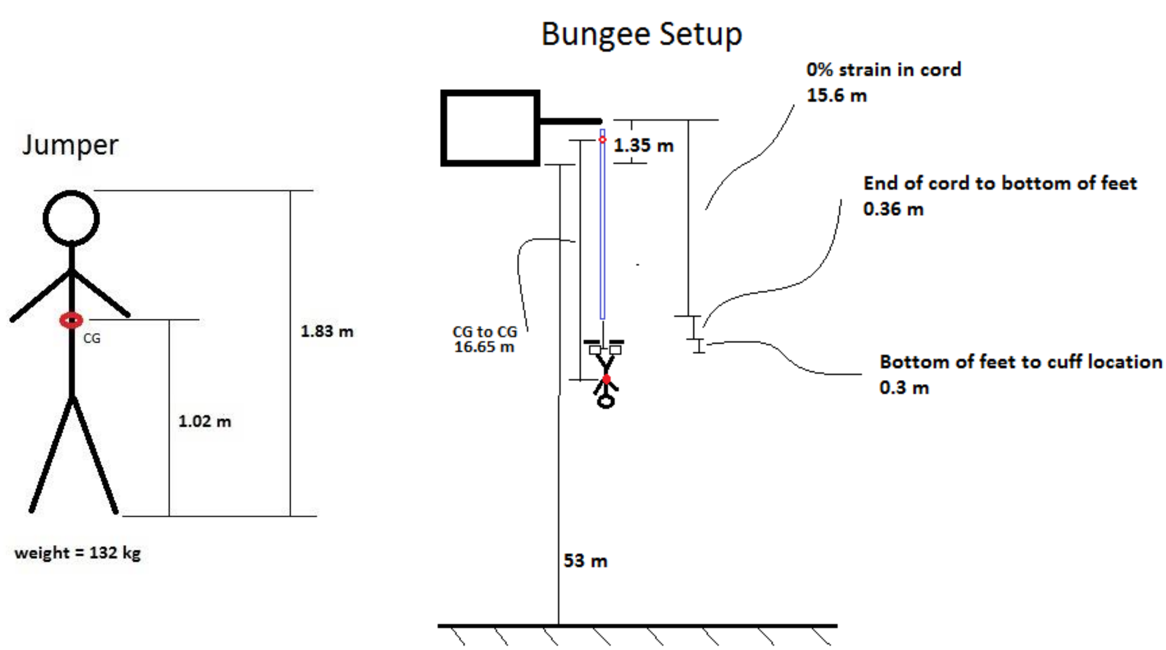

Figure 1: Schematic of jumping setup dimensions and jumper parameters

2.4 Ishikawa Diagram

An Ishikawa diagram, Figure 2, was drawn to identify the possible causes of failure that contributed to the jump accident. In addition to the failures discussed in the investigator's report, other possible failures relating to the environment and prior history of the rope have also been identified and included in this diagram.

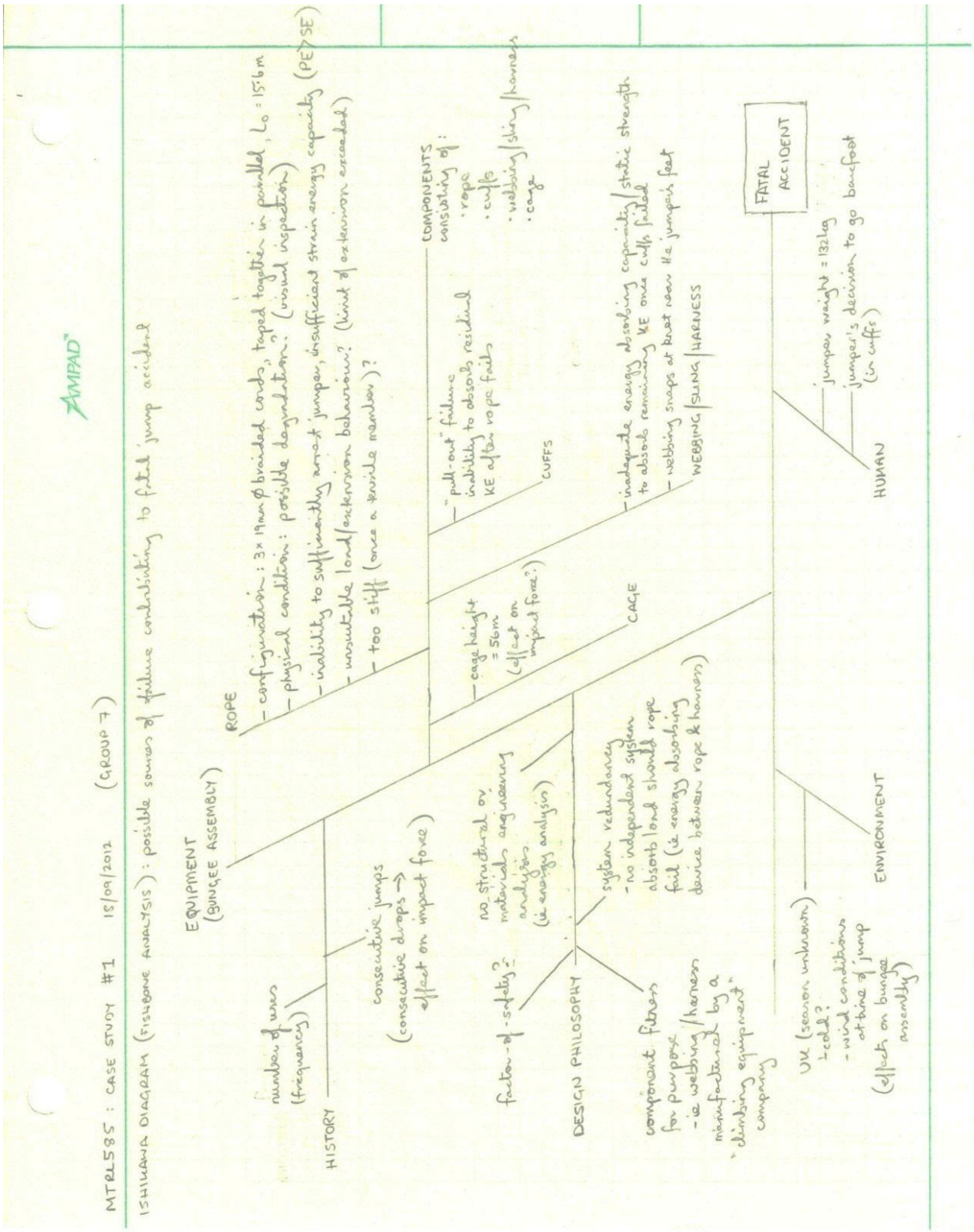

Figure 2: Ishikawa "cause and effect" diagram from jump accident

3.0 ENGINEERING ANALYSIS

The analysis conducted by the author consisted of the following parts:

1. Mechanical testing and inspection of the bungee rope
2. Mechanical testing of safety webbing
3. Energy-based analysis of the failure

To fully understand the approach and concepts used by the author, the analysis was re-created.

3.1 Mechanical Testing of Bungee Rope

The insulating tape and padding were removed from the bungee rope to separate the three cords. One cord was tested in uniaxial tension while measuring the applied load over a 16.0 m extension range (approximately 100% strain). Due to safety concerns, the cord was tested only to 1324 N, rather than to failure. The force-extension behavior for the whole bungee rope was estimated by multiplying the measured force by three. Therefore, the breaking load is assumed to be much higher than the maximum load reached during testing (i.e. greater than 3972 N).

The tensile test data obtained is nonlinear, typical of viscoelastic material response, and has been reproduced as shown in Figure 1. It can be seen here that at high strain values, the cord becomes quite stiff, and minimal additional strain would result in failure. As such, the limit of extension was assumed to be 16.0 m.

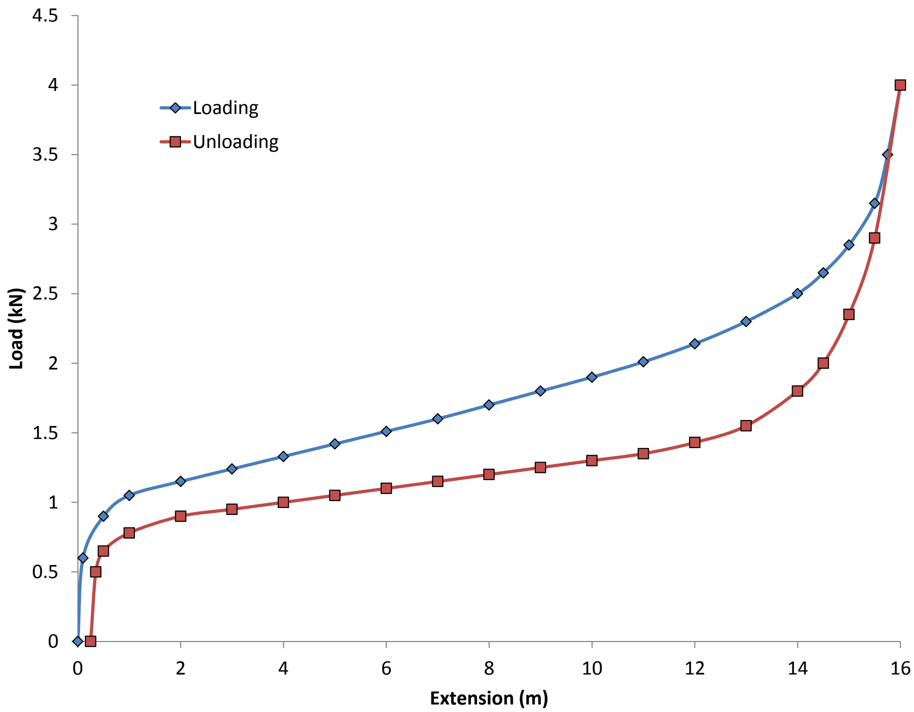

Figure 3: Estimated load-extension behavior of a complete bungee rope

The area under the loading curve represents stored strain energy. For the energy-based analysis of the failure, a mathematical function for the strain energy stored in the rope with respect to its extension is needed. This function is not provided by the author. Thus, to obtain this function, we fitted a 7th order polynomial curve to the load-extension data extracted from the paper, and then integrated it with respect to distance extended in the rope, as shown in Equations (1) and (2).

(1) $$Load(x) = (5.623 * 10^{-7})x^7 - (3.272 * 10^{-5})x^6 + (8.241 * 10^{-4})x^5 + (1.1143 * 10^{-2})x^4 + (9.213 * 10^{-2})x^3 - (4.233 * 10^{-1})x^2 + 1.107x + 1.204 * 10^{-14} \text{ [kN]}$$

(2) $$Strain\ Energy(x) = \int_0^x Load(x)dx = (7.03 * 10^{-8})x^8 - (4.67 * 10^{-6})x^7 + (1.37 * 10^{-4})x^6 - (2.286 * 10^{-3})x^5 + (2.30 * 10^{-2})x^4 - 0.1411x^3 + 0.5535x^2 + 1.204 * 10^{-14}x \text{ [kJ]}$$

In loading up to 16.0 m extension, strain energy of the reproduced fit was found to be 27,653 J. This is within 5% of the value mentioned in the paper (28,660) and was deemed acceptable. The loading curve follows a hysteresis path because energy is dissipated in the form of heat from friction between the rubber filaments. The energy dissipated was estimated as 7579 J, by the difference in area under the loading and unloading curves.

The load-extension data for a new rope consisting of three 19 mm cord, as specified by BS 3F 70, was also reproduced. This was done to compare the performance of a new rope to the accident rope analyzed in the paper. The results of this analysis will be discussed in the critical evaluation section of this report. Figure 3 shows the upper and lower bound lines fitted to the reproduced mechanical testing data of BS 3F 70 and the subsequent equations represent the load and strain energy functions with respect to distance extended in the rope.

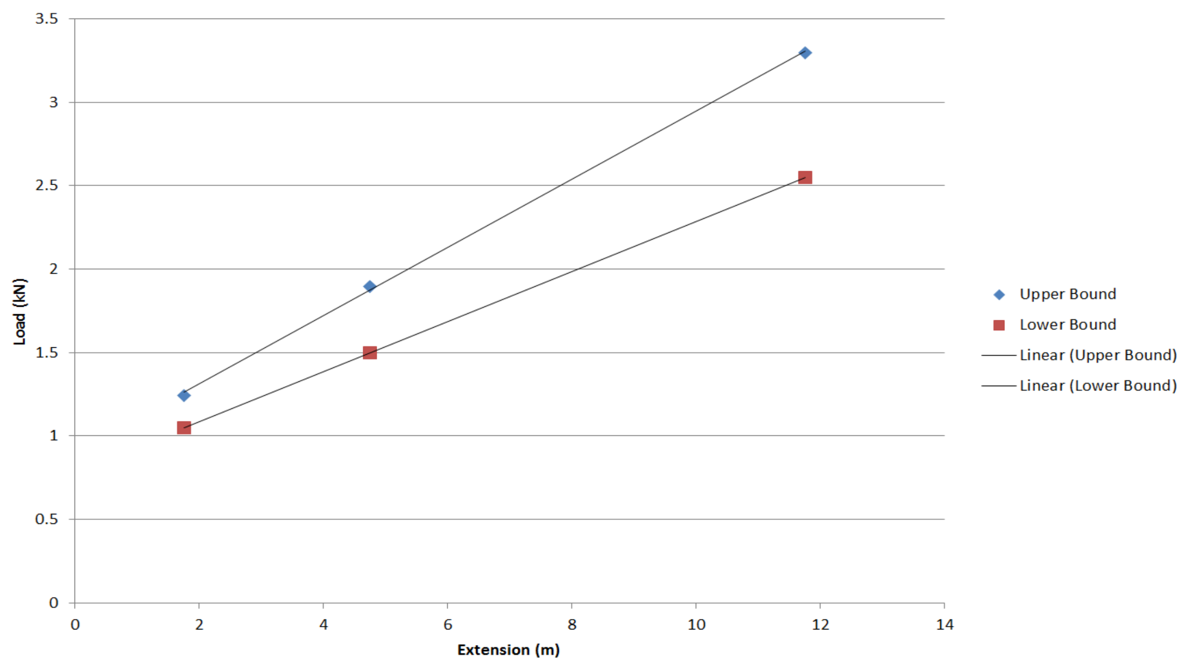

Figure 4: Load-extension behavior of BS 3F 70

Lower Bound:

(3) $Load(x) = 0.15x + 0.7875$

(4) $Strain\ Energy(x) = \int_0^x Load(x)dx = 0.075x^2 + 0.7875x$

Upper Bound:

(5) $Load(x) = 0.2041x + 0.9083$

(6) $Strain\ Energy(x) = \int_0^x Load(x)dx = 0.10205x^2 + 0.9083x$

3.2 Mechanical Testing of Safety Webbing

Safety webbing identical to that involved in the failure was tested in uniaxial tension to failure while measuring applied load and extension. Data has been reproduced as shown in Figure 5. Failure occurred near a knot at a load slightly above 5000 N and extension of approximately 410 mm.

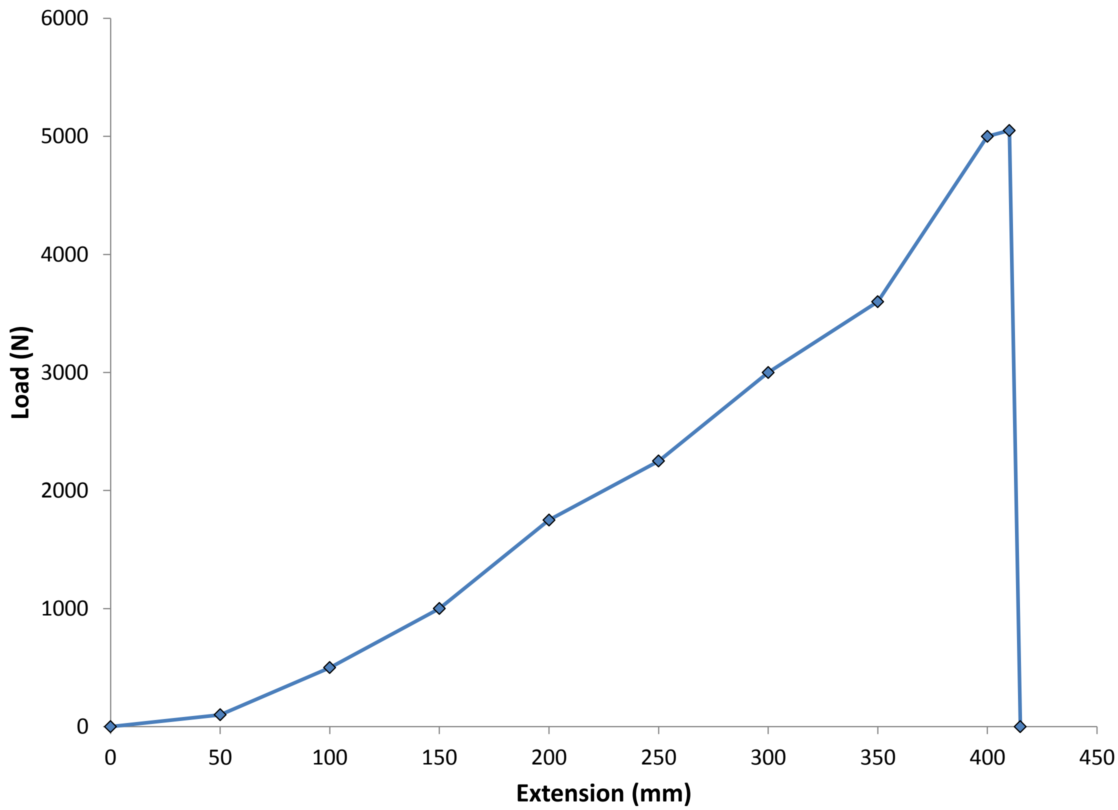

Figure 5: Measured load-extension behavior of safety webbing

3.3 Analysis of Data

The investigator utilized an energy based approach to analyze the mechanics of the jump accident. Using results from the various load-extension plots discussed above, the following engineering analysis has been reproduced:

- Sample hand calculations of selected phases in the jump accident.
- Energy calculation for the accident jump and for different ropes and weights.
- An energy diagram for each of the energy calculations.

Ideally, in a bungee jump event, if the bungee rope is to properly arrest a jumper's fall, then the strain energy capacity of the rope should exceed the potential energy of the jumper. In this particular jump accident, it is shown that the rope used was insufficient, fatally failing to arrest the jumper. This means that the jumper still possessed significant kinetic energy when the rope reached its extension limit. The sample hand calculations presented in section 3.3.1 show the numerical proof for this statement. It also serves as a description of how the important energy and speed values are found in the energy balance tables of section 3.3.2.

3.3.1 Sample Calculations

- Maximum strain Energy (SE) in rope before it reaches limit-of-extension: $SE_{max} = 27653$ J
- Weight of jumper: $W = 132$ kg

$PE = mgh$
$42344 = 132 * 9.81 * h$
$h = 32.7 = (H + \delta)$
$= 16\ (rope\ limit) + 16.7 (distance\ fallen)$

<u>Loss</u> in PE = <u>Gain</u> in kinetic and/or strain energies

$\therefore 42344 = 27653 + KE$
$KE = 14691$ J (a)
$= 0.5mv^2$

$v = \sqrt{\frac{2}{132} * 14691} = 14.9$ m/s → speed the jumper continues to fall at after rope fails to completely absorb energy

If KE = PE

$v = \sqrt{\frac{2}{132} * 42344} = 25.3$ m/s → "free-fall" speed had rope not absorbed any of the fall

% energy absorbed by the rope was:

$$\frac{27653}{42344} = 65\%$$

Cuffs

- Assuming force at rope limit-of-extension ≈ 4 kN (and cuffs pull out) $F_{cuff-release} = 4000$ N
- Distance cuffs "release" $\delta_{cuff} = 0.3$ m

$W = F \cdot \delta = 4000 \cdot 0.3 = 1200$ J
<u>Gain</u> in PE, <u>Loss</u> in KE

$PE = 132 \cdot 0.3 \cdot 9.81 = 388$ J
$KE = W - PE = 1200 - 388 = 812$ J (b)
From (a) and (b)
$KE = 14691 - 812 = 13879$ J

→ $v = 14.5$ m/s
∴ cuff release only slows the jumper's fall by 0.4 m/s

Webbing/climbing sling

Assuming:

- Maximum energy the webbing/sling component can sustain (obtained from mechanical test of component) is: $E_{web} = 940$ J

$KE = 13879$ J

$KE >> E_{web}$ ∴ webbing is not capable of absorbing remaining KE

% arresting capacity: $\frac{940}{13879} \cdot 100 = 7\%$

3.3.2 Energy Tables

The approach used in the sample calculations above for a single position in the jump is replicated for multiple positions throughout the jump to create an energy table. The energy table clearly indicates values for all critical parameters throughout the jump. Contrary to the energy table presented in the paper, the potential energy column of our table represents the instantaneous value of the potential energy of the jumper at any specific height above the ground. The PE column in the paper represented the PE lost after a fallen distance. We found this labeling to be misleading, as the PE *lost* due to a fallen distance differs from the PE *at* a fallen distance. Thus, we included two PE columns in our energy tables to eliminate any confusion. The strain energy at any fallen distance was found using the strain energy equations (2), (4), or (6) depending on which rope is being analyzed (accident rope, lower bound BS 3F 70, or upper bound BS 3F 70, respectively). The KE at any position is the strain energy in the rope subtracted from the PE lost. Finally, the velocity at any position is a function of the KE, as shown in the sample calculations ($v = \sqrt{2 \cdot KE/132}$).

Table 3: Energy calculations (accident case)

Height [m]	Distance fallen [m]	PE [J]	Cumulative PE lost [J]	Rope Extension [m]	SE [J]	KE [J]	Velocity [m/s]	Free fall velocity [m/s]	Time [sec]	TOTAL ENERGY [J]
53	0	68630.76	0			0	0	0	0	68630.76
48	5	62156.16	6474.6			6474.6	9.904544412	9.904544412	1.01	68630.76
43	10	55681.56	12949.2			12949.2	14.00714104	14.00714104	1.43	68630.76
38	15	49206.96	19423.8			19423.8	17.15517415	17.15517415	1.75	68630.76
36.3	16.7	47005.596	21625.164	0	0	21625.164	18.10121543	18.10121543	1.85	68630.76
35.3	17.7	45710.676	22920.084	1	433	22487.084	18.45842339	18.6352891	1.905	68630.76
34.3	18.7	44415.756	24215.004	2	1388	22827.004	18.59741103	19.15447728	1.96	68630.76
33.3	19.7	43120.836	25509.924	3	2572	22937.924	18.64254014	19.65995931	2.014	68630.76
32.3	20.7	41825.916	26804.844	4	3871	22933.844	18.64088208	20.15276656	2.068	68630.76
31.3	21.7	40530.996	28099.764	5	5260	22839.764	18.60260816	20.63380721	2.123	68630.76
30.3	22.7	39236.076	29394.684	6	6740	22654.684	18.52708255	21.1038859	2.177	68630.76
29.3	23.7	37941.156	30689.604	7	8319	22370.604	18.41055527	21.56371953	2.232	68630.76
28.3	24.7	36646.236	31984.524	8	9996	21988.524	18.2526561	22.01395012	2.287	68630.76
27.3	25.7	35351.316	33279.444	9	11764	21515.444	18.0552368	22.45515531	2.343	68630.76
26.3	26.7	34056.396	34574.364	10	13611	20963.364	17.82208538	22.88785704	2.4	68630.76
25.3	27.7	32761.476	35869.284	11	15528	20341.284	17.55566213	23.31252882	2.458	68630.76
24.3	28.7	31466.556	37164.204	12	17514	19650.204	17.25486493	23.72960177	2.516	68630.76
23.3	29.7	30171.636	38459.124	13	19594	18865.124	16.90666177	24.13946975	2.576	68630.76
22.3	30.7	28876.716	39754.044	14	21837	17917.044	16.47635772	24.54249376	2.638	68630.76
21.3	31.7	27581.796	41048.964	15	24410	16638.964	15.87783093	24.93900559	2.701	68630.76
20.3	32.7	26286.876	42343.884	16	27653	14690.884	14.91942196	25.32931108	2.768	68630.76
20	33	25898.4	42732.36	16	28853	13879.36	14.50149418	25.44523531	2.79	68630.76

Table 4: Energy calculations (BS 3F 70 lower bound)

Distance fallen [m]	PE [J]	Cumulative PE lost [J]	Rope Extension [m]	SE [J]	KE [J]	Velocity [m/s]	Free fall velocity [m/s]	Time [sec]	TOTAL ENERGY [J]
0	68630.76	0			0	0	0	0	68630.76
5	62156.16	6474.6			6474.6	9.904544412	9.904544412	1.01	68630.76
10	55681.56	12949.2			12949.2	14.00714104	14.00714104	1.43	68630.76
15	49206.96	19423.8			19423.8	17.15517415	17.15517415	1.75	68630.76
16.7	47005.596	21625.164	0	0	21625.16	18.10121543	18.10121543	1.85	68630.76
17.7	45710.676	22920.084	1	862.5	22057.58	18.28129695	18.6352891	1.905	68630.76
18.7	44415.756	24215.004	2	1875	22340	18.39795937	19.15447728	1.96	68630.76
19.7	43120.836	25509.924	3	3037.5	22472.42	18.45240561	19.65995931	2.014	68630.76
20.7	41825.916	26804.844	4	4350	22454.84	18.44518661	20.15276656	2.068	68630.76
21.7	40530.996	28099.764	5	5812.5	22287.26	18.37622971	20.63380721	2.123	68630.76
22.7	39236.076	29394.684	6	7425	21969.68	18.24483489	21.1038859	2.177	68630.76
23.7	37941.156	30689.604	7	9187.5	21502.1	18.04963863	21.56371953	2.232	68630.76
24.7	36646.236	31984.524	8	11100	20884.52	17.78854074	22.01395012	2.287	68630.76
25.7	35351.316	33279.444	9	13162.5	20116.94	17.45858476	22.45515531	2.343	68630.76
26.7	34056.396	34574.364	10	15375	19199.36	17.05577482	22.88785704	2.4	68630.76
27.7	32761.476	35869.284	11	17737.5	18131.78	16.57480015	23.31252882	2.458	68630.76
28.7	31466.556	37164.204	12	20250	16914.2	16.008617	23.72960177	2.516	68630.76
29.7	30171.636	38459.124	13	22912.5	15546.62	15.34779818	24.13946975	2.576	68630.76
30.7	28876.716	39754.044	14	25725	14029.04	14.57948122	24.54249376	2.638	68630.76
31.7	27581.796	41048.964	15	28687.5	12361.46	13.68557303	24.93900559	2.701	68630.76
32.7	26286.876	42343.884	16	31800	10543.88	12.63945482	25.32931108	2.768	68630.76
33	25898.4	42732.36	16	31800	10932.36	12.87019107	25.44523531	2.79	68630.76

Table 5: Energy calculations (BS 3F 70 upper bound)

Distance fallen [m]	PE [J]	Cumulative PE lost [J]	Rope Extension [m]	SE [J]	KE [J]	Velocity [m/s]	Free fall velocity [m/s]	Time [sec]	TOTAL ENERGY [J]
0	68630.76	0			0	0	0	0	68630.76
5	62156.16	6474.6			6474.6	9.904544412	9.904544412	1.01	68630.76
10	55681.56	12949.2			12949.2	14.00714104	14.00714104	1.43	68630.76
15	49206.96	19423.8			19423.8	17.15517415	17.15517415	1.75	68630.76
16.7	47005.596	21625.164	0	0	21625.16	18.10121543	18.10121543	1.85	68630.76
17.7	45710.676	22920.084	1	1010.35	21909.73	18.21992499	18.6352891	1.905	68630.76
18.7	44415.756	24215.004	2	2224.8	21990.2	18.25335337	19.15447728	1.96	68630.76
19.7	43120.836	25509.924	3	3643.35	21866.57	18.20197042	19.65995931	2.014	68630.76
20.7	41825.916	26804.844	4	5266	21538.84	18.06505248	20.15276656	2.068	68630.76
21.7	40530.996	28099.764	5	7092.75	21007.01	17.84063034	20.63380721	2.123	68630.76
22.7	39236.076	29394.684	6	9123.6	20271.08	17.52534269	21.1038859	2.177	68630.76
23.7	37941.156	30689.604	7	11358.55	19331.05	17.11416833	21.56371953	2.232	68630.76
24.7	36646.236	31984.524	8	13797.6	18186.92	16.59998357	22.01395012	2.287	68630.76
25.7	35351.316	33279.444	9	16440.75	16838.69	15.97284343	22.45515531	2.343	68630.76
26.7	34056.396	34574.364	10	19288	15286.36	15.21879022	22.88785704	2.4	68630.76
27.7	32761.476	35869.284	11	22339.35	13529.93	14.31778614	23.31252882	2.458	68630.76
28.7	31466.556	37164.204	12	25594.8	11569.4	13.23986405	23.72960177	2.516	68630.76
29.7	30171.636	38459.124	13	29054.35	9404.774	11.93719296	24.13946975	2.576	68630.76
30.7	28876.716	39754.044	14	32718	7036.044	10.32505338	24.54249376	2.638	68630.76
31.7	27581.796	41048.964	15	36585.75	4463.214	8.223408937	24.93900559	2.701	68630.76
32.7	26286.876	42343.884	16	40657.6	1686.284	5.054676802	25.32931108	2.768	68630.76
33	25898.4	42732.36	16	40657.6	2074.76	5.606759989	25.44523531	2.79	68630.76

Table 6: Excerpt energy calculations (accident case, variants for 90 and 70 kg body weights)

Height [m]	Distance fallen [m]	Rope Extension [m]	SE [J]	PE for 90 kg [J]	Cumulative PE lost for 90 kg [J]	PE for 70 kg [J]	Cumulative PE lost for 70 kg [J]
26.3	26.7	10	13611	23220.27	23573.43	18060.21	18334.89
25.3	27.7	11	15528	22337.37	24456.33	17373.51	19021.59
24.3	28.7	12	17514	21454.47	25339.23	16686.81	19708.29
23.3	29.7	13	19594	20571.57	26222.13	16000.11	20394.99
22.3	30.7	14	21837	19688.67	27105.03	15313.41	21081.69
21.3	31.7	15	24410	18805.77	27987.93	14626.71	21768.39
20.3	32.7	16	27653	17922.87	28870.83	13940.01	22455.09

3.3.3 Energy Diagrams

The energy diagrams presented in this section are a graphical representation of the energy calculation tables in section 3.32. These diagrams can be used to visually observe differences between energy values and, thus, quickly identify the performance of the rope. After discussion within our group regarding the energy diagrams the author presents in his paper, we've decided to change his diagram layout. We disagree with his layout for two reasons:

- The PE in the author's diagrams start at zero at the beginning of the jump, although it should actually be at its highest value there. The fact that the PE line the author uses represents the PE *lost* during the jump is not clear whatsoever.
- The KE in the author's diagrams is shown to be the area under the PE line, which is not correct. Furthermore, there is no specific line representing the KE of the jumper.

The alternative layout we use in this section do not have these problems and clearly illustrate the multiple energy forms throughout the jump. Moreover, the total energy line can be plotted to serve as a verification that the energy balance is correct. Also, using the layout we presented, the suitability of the rope can be determined by either checking whether the KE reaches zero throughout the jump or whether the SE equals the sum of the KE and PE at any moment in the jump.

Figures 5-7 are the energy diagrams for the various rope cases presented in section 3.3.2. Regarding the velocity vs. distance plot presented by the author in the paper, our group did not find it very important from a practical sense. It's not very important to know the exact numerical velocity value of the jumper all throughout the jump. It is sufficient to observe the velocity value at the limit-of-extension of the rope. Similarly, the time vs. distance plot presented does not add any new dimension to the analysis. For this reason, these two graphs were deemed irrelevant and were not reproduced.

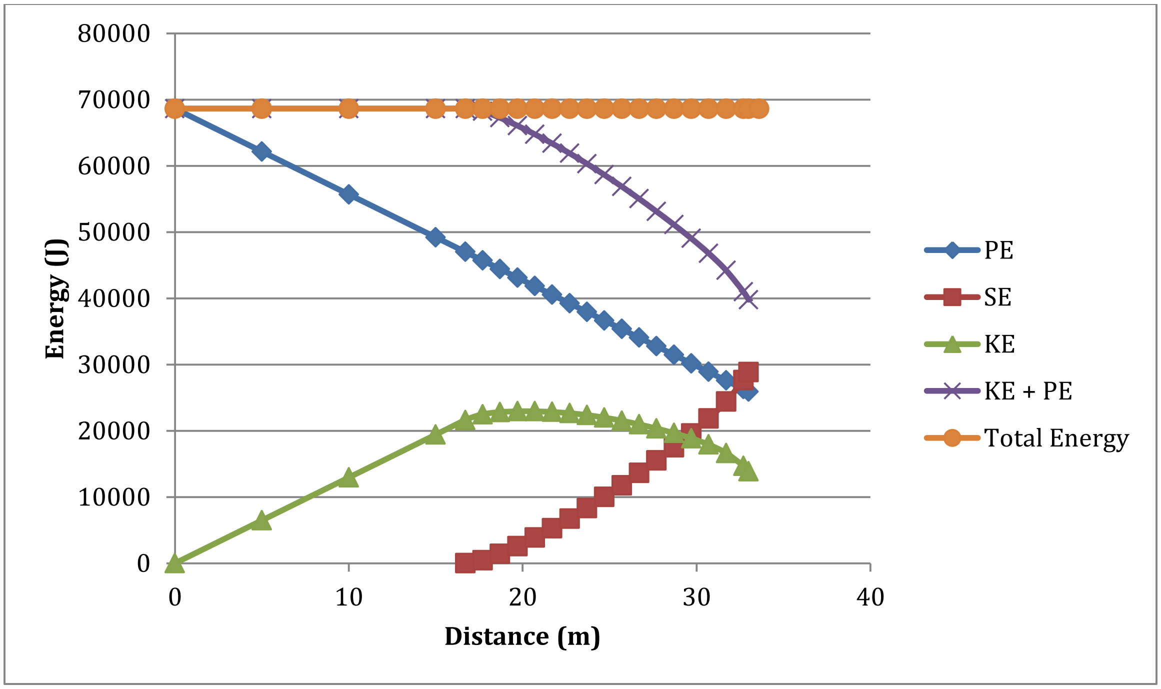

Figure 6: Energy diagram for accident case

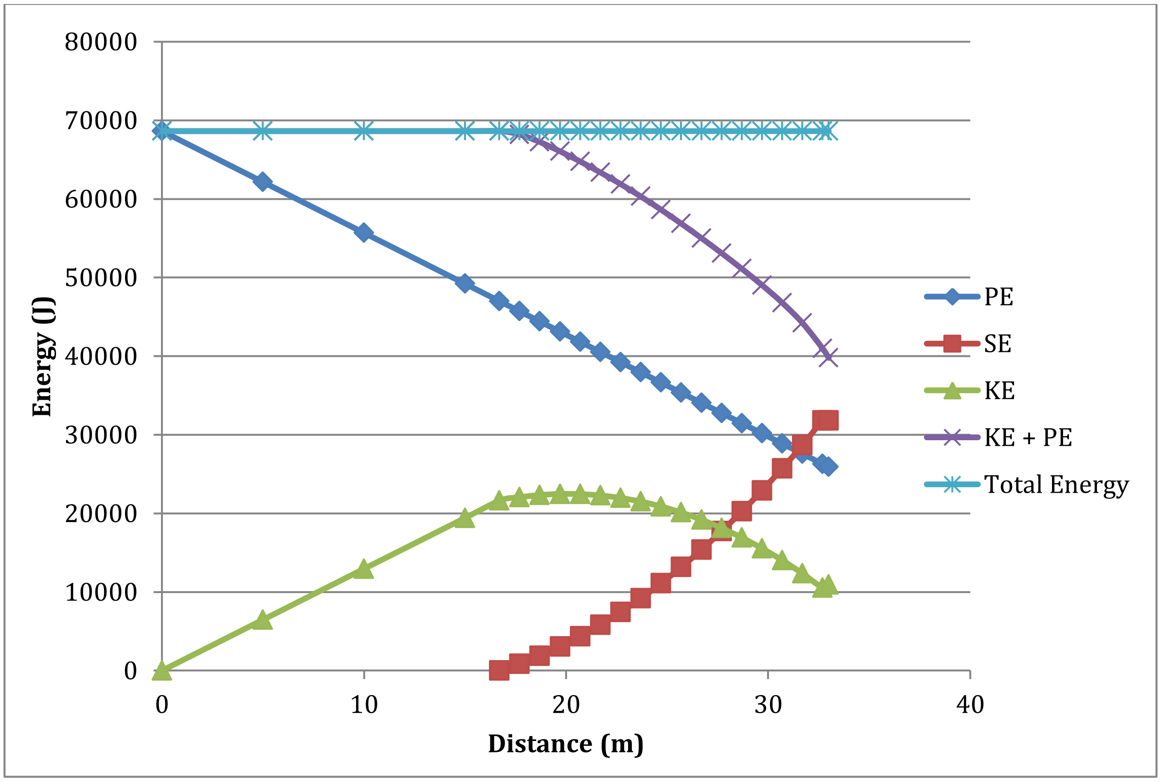

Figure 7: Energy diagram for BS 3F 70 lower bound

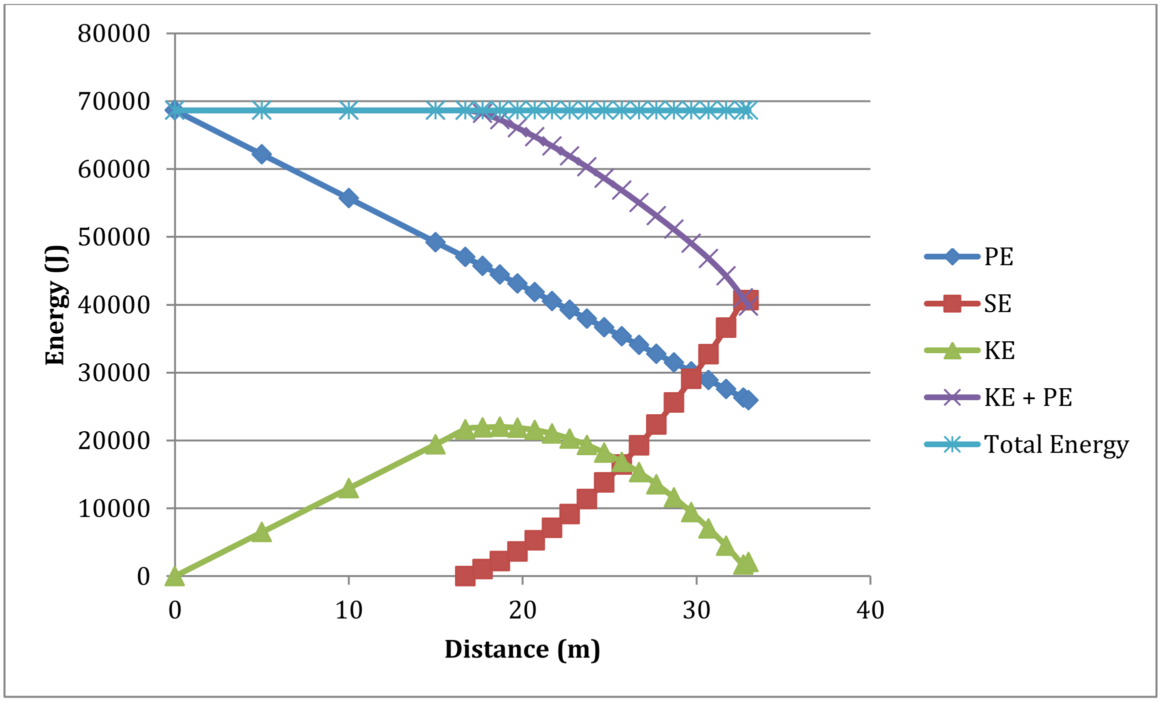

Figure 8: Energy diagram for BS 3F 70 upper bound

3.3.4 Discussion – Jump Accident

- The rope was only capable of sustaining 65% of the jumper's potential energy, at which time the jumper's estimated velocity was 14.9 m/s;
- It was shown that the cuffs contributed negligibly to arresting the jumper once the rope failed, slowing the jumper down to approximately 14.5 m /s;
- The safety webbing was shown to have approximately 7% capacity in sustaining the remaining potential energy in the system once the cuffs had pulled-out, clearly inadequate;
- The estimated force in the cuffs was 4 kN (an approximate g-force = 3 g) so the jumper may have sustained a serious injury had the cuffs not pulled-out;
- Had the jumper's bungee assembly been fitted with an additional energy absorbing device, he may have survived the fall and only sustained less serious injuries;
- Given the configuration of the accident jump rope and the data supplied in the report, the maximum weight that could have been sustained by the rope is only 90 kg (approximately 40 kg lighter than the jumper's weight), raising the question: why was this particular person allowed to jump using this rope?
- The maximum jump distance in the accident jump case was approximately 32 m ($L_o + L_{lim}$) however the cage height was 53 m, why was the cage height set so high as this height would contribute to the impact force?

3.3.5 G-force Analysis

A simplified analysis of possible G-forces the jumper may have experienced had the cuffs not "slid" off is presented. The forces involved are analyzed for the actual case, lower, and upper boundary cases for the strain energy of the bungee cord. No information is given on the possible strain energy of the cuff attachment involved in the actual jump; therefore the small reduction of kinetic energy is ignored in this analysis. The equations used in the analysis are the following:

1. ${V_f}^2 = {V_i}^2 + 2ad$ → solved for acceleration, V_f = 0, Vi known from energy calculations, d is assumed and ranges from .05 to 1.0 m
2. $V_f = V_i + at$ → solved for time, V_f = 0, V_i known from energy calculations, a taken from equation (1).
3. $F = ma$ $\quad\quad m = 132$ kg
4. G-force = $F/(gm)$

The initial velocity used in each equation was taken from the energy calculations of section 3.32. The initial velocity is taken immediately before the cuff begins to slip as to model a situation in which the cuff hadn't slipped at all. It is shown that even allowing for a 1.0 m extension in the cuff only a bungee cord possessing the strain energy of the upper boundary limit for 3 x 19 mm cord would have produced a survivable G-force upon the arrest of the jumper. This is assuming that the cuffs, unlike the safety webbing, could support the force at impact. The G-force results suggest that the bungee used in this case was simply not capable of supporting the jumpers' weight, especially with any degradation of the cord.

Table 7: Cuff g-force analysis for accident case

$V_i = 14.919\ m/s$

Extension (m)	Acceleration (m/s^2)	Time to stop (s)	Force (N)	G-Force
1	-111.2882805	0.134057242	-14690.1	-11.3444
0.95	-117.1455584	0.12735438	-15463.2	-11.9414
0.9	-123.653645	0.120651518	-16322.3	-12.6049
0.85	-130.9273888	0.113948656	-17282.4	-13.3463
0.8	-139.1103506	0.107245794	-18362.6	-14.1805
0.75	-148.384374	0.100542932	-19586.7	-15.1258
0.7	-158.9832579	0.09384007	-20985.8	-16.2062
0.65	-171.2127392	0.087137208	-22600.1	-17.4529
0.6	-185.4804675	0.080434345	-24483.4	-18.9073
0.55	-202.3423282	0.073731483	-26709.2	-20.6261
0.5	-222.576561	0.067028621	-29380.1	-22.6887
0.45	-247.30729	0.060325759	-32644.6	-25.2097
0.4	-278.2207013	0.053622897	-36725.1	-28.3609

0.35	-317.9665157	0.046920035	-41971.6	-32.4125
0.3	-370.960935	0.040217173	-48966.8	-37.8146
0.25	-445.153122	0.033514311	-58760.2	-45.3775
0.2	-556.4414025	0.026811448	-73450.3	-56.7219
0.15	-741.92187	0.020108586	-97933.7	-75.6291
0.1	-1112.882805	0.013405724	-146901	-113.444
0.05	-2225.76561	0.006702862	-293801	-226.887

Table 8: Cuff g-force analysis for BS 3F 70 lower bound

$V_i = 12.693\ m/s$

Extension (m)	Acceleration (m/s^2)	Time to stop (s)	Force (N)	G-Force
1	-79.8721605	0.158240367	-10543.1	-8.14191
0.95	-84.07595842	0.150328349	-11098	-8.57043
0.9	-88.746845	0.14241633	-11714.6	-9.04657
0.85	-93.96724765	0.134504312	-12403.7	-9.57872
0.8	-99.84020063	0.126592294	-13178.9	-10.1774
0.75	-106.496214	0.118680275	-14057.5	-10.8559
0.7	-114.1030864	0.110768257	-15061.6	-11.6313
0.65	-122.8802469	0.102856239	-16220.2	-12.526
0.6	-133.1202675	0.09494422	-17571.9	-13.5699
0.55	-145.22211	0.087032202	-19169.3	-14.8035
0.5	-159.744321	0.079120184	-21086.3	-16.2838
0.45	-177.49369	0.071208165	-23429.2	-18.0931
0.4	-199.6804013	0.063296147	-26357.8	-20.3548
0.35	-228.2061729	0.055384128	-30123.2	-23.2626
0.3	-266.240535	0.04747211	-35143.8	-27.1397
0.25	-319.488642	0.039560092	-42172.5	-32.5676
0.2	-399.3608025	0.031648073	-52715.6	-40.7096
0.15	-532.48107	0.023736055	-70287.5	-54.2794
0.1	-798.721605	0.015824037	-105431	-81.4191
0.05	-1597.44321	0.007912018	-210863	-162.838

Table 9: Cuff-g-force analysis for BS 3F 70 upper bound

$V_i = 5.054\ m/s$

Extension (m)	Acceleration (m/s^2)	Time to stop (s)	Force (N)	G-Force
1	-12.771458	0.395726157	-1685.83	-1.30188
0.95	-13.44364	0.37593985	-1774.56	-1.3704

0.9	-14.19050889	0.356153542	-1873.15	-1.44654
0.85	-15.02524471	0.336367234	-1983.33	-1.53163
0.8	-15.9643225	0.316580926	-2107.29	-1.62735
0.75	-17.02861067	0.296794618	-2247.78	-1.73584
0.7	-18.24494	0.27700831	-2408.33	-1.85983
0.65	-19.64839692	0.257222002	-2593.59	-2.00289
0.6	-21.28576333	0.237435694	-2809.72	-2.1698
0.55	-23.22083273	0.217649387	-3065.15	-2.36706
0.5	-25.542916	0.197863079	-3371.66	-2.60376
0.45	-28.38101778	0.178076771	-3746.29	-2.89307
0.4	-31.928645	0.158290463	-4214.58	-3.2547
0.35	-36.48988	0.138504155	-4816.66	-3.71966
0.3	-42.57152667	0.118717847	-5619.44	-4.33961
0.25	-51.085832	0.098931539	-6743.33	-5.20753
0.2	-63.85729	0.079145231	-8429.16	-6.50941
0.15	-85.14305333	0.059358924	-11238.9	-8.67921
0.1	-127.71458	0.039572616	-16858.3	-13.0188
0.05	-255.42916	0.019786308	-33716.6	-26.0376

4.0 CRITICAL EVALUATION

The author has presented a logical approach to the failure investigation, and has developed reasonable conclusions. However, potential for improvement has been identified in areas described in the following sections.

4.1 Missing Background Information

Climate

The author did not address the climate in which failure occurred. As the country and date were not reported, a temperature cannot even be inferred based on historical climate data. Figure 8 shows temperature dependence of shear modulus (typically proportional to tensile modulus) for natural rubber having various degrees of vulcanization [4]. Since the ability to absorb strain energy (i.e. stiffness) is a function of temperature, lab tests should be performed at the same temperature as that in which the incident occurred.

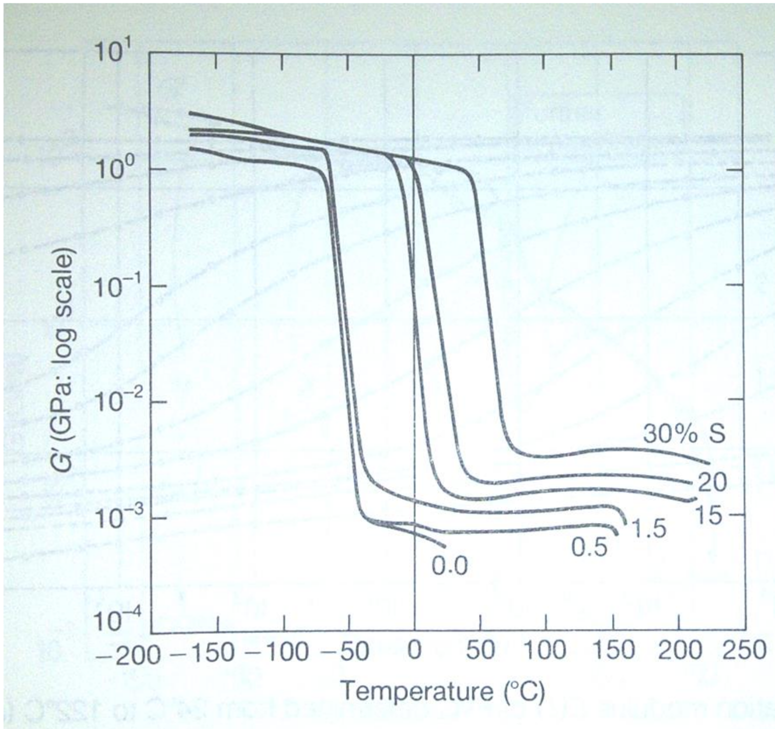

Figure 9: Temperature dependence of shear modulus of natural rubber for varying degrees of vulcanization [4]

Visual Inspection of Rope

The first step of most failure investigations is a detailed visual inspection. In Section 2.2, "Examination and testing of bungee rope", the author does not comment on the condition of the cord filaments or bungee rope sheathing. Details such as external wear or UV degradation may imply that the rope was heavily used or the rubber had degraded. Alternatively, a comments indicating that it was in immaculate condition may support conclusion of his energy-based model.

4.2 Mechanical Testing

All strain energy calculations were based on results from the tensile test of a single bungee cord. As many factors will influence the mechanical response of rubber, it is important to develop statistical confidence by performing multiple tests.

Tensile properties of rubber are also known to be sensitive to strain rate [5], which was not reported for the tensile tests on the bungee cord. As shown in Figure 109, nitrile rubber will follow very different deformation paths depending on the strain rate. Method of load application was also omitted, so strain rate cannot be estimated. The jumper's velocity during the tensioning of the bungee rope ranged from 0.92 s^{-1} to 1.18 s^{-1}. Since a travel of 16.0 m would likely require a winch or crane, the strain rate of testing would likely be less than 0.006 s^{-1} (0.1 m/s).

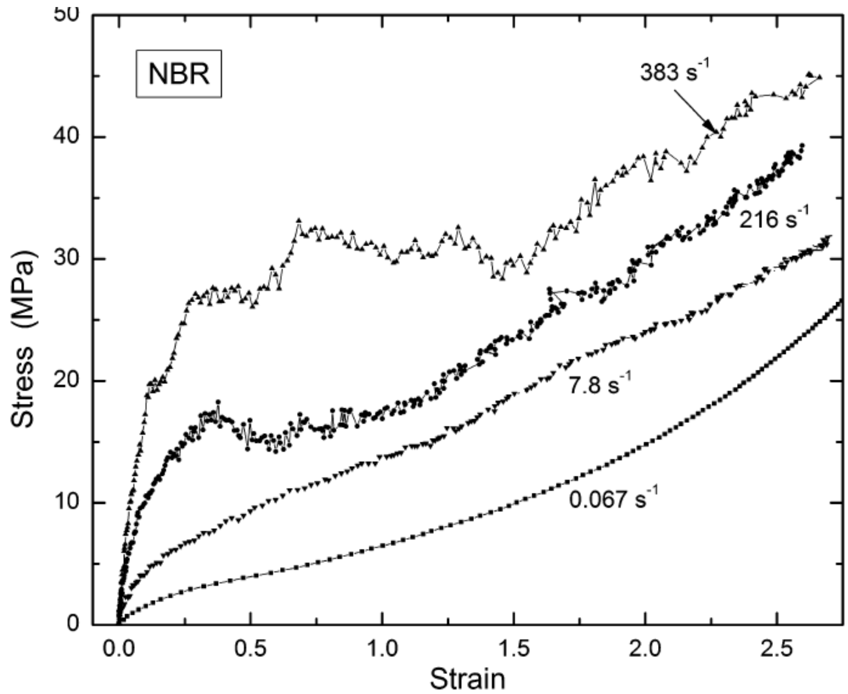

Figure 10: Stress-strain curves for nitrile rubber at various strain rates [5]

4.3 Accident Prevention

Bungee-jumping is an inherently dangerous activity. The consideration of safety is critical to ensuring future jump accidents are prevented. Key aspects underpinning the safe participation in a bungee-jumping event are the design and condition of the jump equipment. Factors such as normal usage, wear and environmental aging can also detrimentally affect safety [3].

The investigator, in Sections 3, 4 and 5 of his report [1], outlines some measures to prevent future jump accidents, including:

- The use of energy calculations to determine minimum jump rope design and maximum permissible deceleration force;
- Independent system redundancy, such as fitting an energy-absorbing device between the jumper's harness and rope.

Table 10 summarizes important criteria to be considered in such accident prevention. Many of these important criteria are not necessarily mutually exclusive.

Table 10: Key considerations to avoid future jump accidents

Jump Equipment	mechanical design
	materials / component selection
	expected loads / load cases (configuration)
Operation / Use	condition of the equipment
	governing codes of practice / design codes
	operator conduct (adherence to guidelines)
	jumper behavior and technique

Mechanical Design

- Factors-of-safety: maintaining integrity whilst allowing for 'in-service' degradation;
- Intended design life of the system (materials and components);
- Determination of critical design drivers (trade-offs), such as: weight of assembly (jumper and rope) and rope (compliance and flexibility);
- Design decisions (historically based on empirical 'trial-and-error' approach) are evolving to analytical (energy based) approaches;
- Structural redundancy: activated to prevent serious injury to a jumper should the rope fail, examples:
    - energy-absorbing devices fitted on jumper;
    - force / velocity sensors fitted at the cage to detect when to feed out extra rope if limits in impact force or speed are reached;
    - a secondary rope that deploys when the primary rope fails.

Materials and Component Selection

- Rope material viscoelastic properties:
    - strain energy capability and capacity;
    - load-extension tests (such as BS 3F 70) and consideration of strain-rate;
    - temperature dependence.
- End-connector devices ('snap-hooks', karabiners):
    - component load-ratings: selection of devices that are 'fit-for-purpose' and have sufficient static strength.

Expected Loads and Load Cases

- Mechanical tests to determine likely impact loads and validate analytical analyses such as deadweight drop tests;
- Minimizing load uncertainty due to factors such as:
    - changing rope length (and cage height);
    - fall factors (H/l ratio) [3];
    - repeat jumps and rest periods [3].

Operation / Use of Equipment

- Operators have a 'duty of care' and to some extent should have an appreciation for the key operating parameters of the bungee equipment / configuration they operate. For instance:
  - an awareness of what a fall factor is (H/l ratio) [3] and its impact on jumper safety;
  - setting an appropriate cage height;
  - knowing the limitations of the jump ropes used, for instance the maximum jump weight;
  - jumpers also have a 'duty of care' to ensure that they also take reasonable measures to safeguard their jump including wearing appropriate clothing, perhaps overalls, and shoes;
  - be aware of the risks associated with bungee-jumping.

Governing Codes of Practice / Design Codes

- Records / logs should be maintained to keep a record of the in-service history of the jump equipment
- Inspection schedules should be maintained:
  - visually inspect the condition of the equipment
  - perform routine maintenance or servicing
- Governing bodies such as the British Elastic Rope Sports Association (BERSA) and Health and Safety Executive / Local Authorities Enforcement Liasion Committee (HELA) should establish:
  - energy-based minima criteria, for instance: the minimum energy absorbing capacity for harness connections
  - agree with the principle of the testing rope cords at strain intervals to get an appreciation of the rope degradation
  - procedures for destroying ropes as ropes should be considered 'lifed components' which should be destroyed once they have reached limits such as age and/or a given number of jumps

4.4 Format and Presentation

There are many ideas presented in this paper, which is often difficult to organize in an efficient manner. In earlier sections, alternate methods were used to express ideas and data, but there are other areas that may have also benefitted from some modification. Following are ideas for improving the format and presentation of this failure analysis:

- Although most data was made available to the reader, figures contained data that was not explained until much later in the report. This can be quite confusing, as it clutters the graphs making them difficult to interpret. A simple solution is to revise the graph with new information in later sections where the ideas are re-visited.

- The schematic diagram appeared slightly unprofessional, which may mislead some readers. For example, the drawing shows a "slack bungee rope" that may be able to be lengthened without stretching. This would contradict the length measurement of 15.6 m.
- The force-extension curve for the bungee rope has only 7 points plotted along the loading portion. Since the strain energy is an important part of the analysis, and it was calculated from this data, it would have been wise to log more data. Also, the unloading data was not used in the analysis. The author acknowledges an energy loss during unloading, but does not report this value.
- The point at which all slack is removed from the rope is an important, yet simple detail, and was presented in a table but the origin was not explained. The author does not explain that this is the sum of the length of the rope (15.6 m), twice the height of the jumper's center of gravity (2 x 1.02 m), and the length of the cuff assembly (0.36 m), minus the height of the rope's attachment point above the cage floor (1.35 m).
- Since a mathematical method of energy balance was used for the analysis, the basic equations should be reviewed and provided in the body of the text. Instead, the most important equations were included as a footnote of the tabulated data.
- In Section 2.7, "Force/extension curve of bungee rope", the author re-visits the load extension behavior and expectations of the rope. This information validates and expands on earlier notions in Section 2.2 and would fit well in that section.
- The leg cuffs were very vaguely described as being "pulled tight around the lower legs". The author should better describe "lower legs" as either ankles or calves, as there is a critical difference.
- The author also generically describes the trouser material as smooth without citing coefficient of friction, and claims that the trousers contributed to release of the cuffs. Assuming that the cuffs were fastened to the ankles (a practice common in bungee jumping), he may have recommended that the cuffs be fastened beneath the jumper's pants, directly against his skin. Fastening cuffs at a location other than the ankles or overtop of trousers at the ankles would be a failure in implementing or following safe procedures.

5.0 CONCLUSION

- In reproducing the key analysis, the group has been able to demonstrate that the accident rope was insufficiently capable of arresting the jumper. Calculations showed that the rope was capable of absorbing 65% of the loss in potential energy, at which point the jumper's velocity was estimated to be 14.9 m/s.
- The group also demonstrated that regardless of the possible degradation of the rope, it was the jumper's weight and subsequent g-forces sustained that contributed to the accident.
- The use of an energy-based analysis is a sound approach with respect to investigating this accident. However, as discussed in the previous section, the group felt that the investigator's analysis was sometimes misleading and contradictory. The investigator's report was verbose and confusing, thus difficult to understand in some sections.
- Bungee jumping is a dangerous activity and thus robust equipment design is critical to ensuring the safety of the jumper whilst making the experience a pleasurable one. A key aspect of this design is the characterization of the jump rope and knowing its limits with respect to strain energy capacity and the likely impact forces it will experience during its in-service life.

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