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A5 1 Rollercoaster Restraint vs Your Spine

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Abstract

We investigate the plausibility of falling out of a restraint mid-ride. We determine that a rider would need to exert 35 kN of force (45 Gs of G-force) to the contact, causing the pawls to fail by mode of buckling. At this force, we find the human torso would extend by 7 metres. We find a human would break before the restraint would.

Introduction

Rollercoasters provide a thrilling experience with a whole host of forces for riders to enjoy. However, many people worry about falling out of a rollercoaster due to a restraint failure mid-ride. Any high-class restraint must be dependable and only release intentionally [1]. So the only reasonable way for this scenario to occur would be a material failure within the restraint due to high forces (pushing the rider into the restraint and breaking its weakest part). We looked into the forces required for this to occur. We then compared them to the strength of the human body, to determine what would break first: the restraint or you.

Breaking the Restraint

We have modeled our restraint based of Bolliger and Mabillard's "clamshell" restraint, using a ratchet system for locking (as shown in *Figure 1*). We assume that the first subcomponent to break due to extreme force would be the pawl holding the ratchet in place, as a similar look into restraint mechanics [2] determined it to have the lowest breaking force to yield. We have assumed two parallel ratchet and pawl systems as per redundancy found in high-class restraints. Together, having combined effective dimensions of 4 × 1 × 8cm (see *Figure 2* for orientation). Because of their length, failure due to buckling can be assumed. Combining Euler's buckling formula and moment of inertia for our cuboid gives:

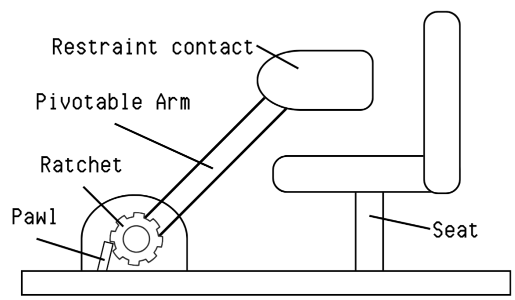

Figure 1: The restraint setup, locked at a 45°.

$$P_{crit} = \frac{\pi^2 E}{(KL)^2} \cdot \frac{bh^3}{12} \tag{1}$$

Where $E_{St} = 200$ GPa is Young's Modulus [3], $K = 2$ is effective length multiplier as it is fixed at one end, $L = 8$cm is length in direction of force, $b = 4$cm is width and $h = 1$cm is height. Giving $P_{crit} = 250$kN as critical buckling load.

The scenario of choice is the feeling of being pulled out of your seat by going over a small 'air-time' hill with great speed. For this we treated the ratchet's bearing as the pivot point for determining the force perpendicular to the pivot, then resolved the total force due to rider F.

$$F = \sqrt{2(\frac{d_1 P_{crit}}{d_2})^2} \tag{2}$$

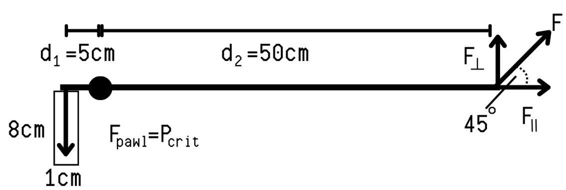

Figure 2: A simplified moments diagram

We calculated $F = 35$ kN, the equivalent G-force acceleration (assuming 80 kg passenger as per ASTM 2291 standards [1]) being 45 Gs. On amusement rides, the highest G-force legally permitted is 6 Gs and only for 1 second[1]. Negative G-forces, such as in this scenario are limited to -2 Gs for 0.2 seconds[1]. No legal amusement ride even approaches this force.

Breaking you

We then used this force as a baseline to compare with how the human body would withstand. We modeled the torso as having two key tensile components, the spine and skeletal muscle. The spine has a tensile strength of $E_{Sp} = 2.3$ MPa [4] and an area of $A_{Sp} = 4\text{cm}^2$. The combined skeletal muscle system has a tensile strength of $E_M = 0.44$MPa [5] and an area of $A_M = 50\text{cm}^2$. Treating these as parallel systems, we can deduce an effective tensile strength of $E_T = 0.58$MPa of the area, $A_T = 54\text{cm}^2$. If we model the torso as a cylinder with a length of $L = 0.65$m, then under a force of $F = 35$kN, the torso would extend by $\Delta L = 7$m. This analysis may be pessimistic, as exposure to the high force would likely be brief. However, you would also need to give the pawl that stipulation, which we haven't.

Being stretched to over 10x original length would undeniably kill the average human. A person's upper and lower torso would no longer be connected.

Conclusion

Our model suggests you would break far before the restraint. The high 35kN threshold in order to cause restraint failure would far exceed human limits. At the necessary force to break, you'd die due to a torso extension of 7 metres. This level of force is impossible on any registered and legal rollercoaster. Therefore, If you think your body can withstand a rollercoaster, your restraint definitely can.

References

[1] ASTM F2291-24: Standard Practice for Design of Amusement Rides and Devices, ASTM International, West Conshohocken, PA, USA, 2024.

[2] Griffin Schobel, *Rollercoaster Restraint System* (2019) `https://griffinschobel.com/rollercoaster-restraint-system` [Accessed 10 October 2024]

[3] W. E. Luecke et al, *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Mechanical Properties of Structural Steels*, NIST NCSTAR 1-3D, National Institute of Standards and Technology, Gaithersburg, MD, 2005.

[4] Stemper BD et al. *Biomechanical properties of human thoracic spine disc segments.* J Craniovertebr Junction Spine. 2010 Jan;1(1):18-22. doi: 10.4103/0974-8237.65477. PMID: 20890410; PMCID: PMC2944859.

[5] Kuthe CD et al. *Experimental evaluation of fiber orientation based material properties of skeletal muscle in tension.* Mol Cell Biomech. 2014 Jun;11(2):113-28. PMID: 25831858.