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Investigation of Hyperloop Skeleton Tube Design

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Abstract

The Hyperloop Skeleton tube design is the latest addition to the integral designs that holds great potential in terms of weight efficiency. The aim of this research is to determine the applicability and efficiency of the newly proposed hyperloop tube design and to evaluate structural performance to imposed loads.
Based on numerical results, the skeleton tube design is conditionally satisfactory in terms of ultimate and serviceability limit states. The design can resist the main load case – vacuum pressure. Nevertheless, the slender components and thin plates make the tube susceptible to plate rupture or penetration if exposed to environmental actions; thus, making the hyperloop system vulnerable to accidental and impact loads.

Keywords: hyperloop, hyperloop infrastructure, skeleton tube design, European Hyperloop Center, lightweight tube design, slender steel structure, detail engineering.

1 Introduction

As the hyperloop technology is still under development, and the infrastructure has yet to exist, it gives the opportunity to research, optimise, and develop hyperloop concepts thoroughly. The tube design is of great importance for safety and for ensuring a flawless operation. It also has a significant environmental impact, considering the predicted total length of the infrastructure. Currently new designs are constantly being developed, and based on detailed and thorough risk analysis, it may become feasible to design a lightweight tube that still meets safety requirements. This could lead to material weight savings and, subsequently, a decreased environmental impact.

2 Methodology and objectives

The main objective of this research is to assess a new hyperloop tube design in terms of ultimate and serviceability limit states. Moreover, to identify weaknesses and modify the design appropriately to mitigate potential failure modes.

An analytical approach was conducted to verify the design choices. Following this, Finite Element (FE) models were made and analysed. Based on FEA results, several issues have been addressed, such as stress concentrations at connections and initiation of plastic response. The report also includes a proposed solution for the rails supports and a ring-to-stringer connection design. Additionally, the design performance is evaluated in a comparative study with the existing plain tube design, which serves as the benchmark design.

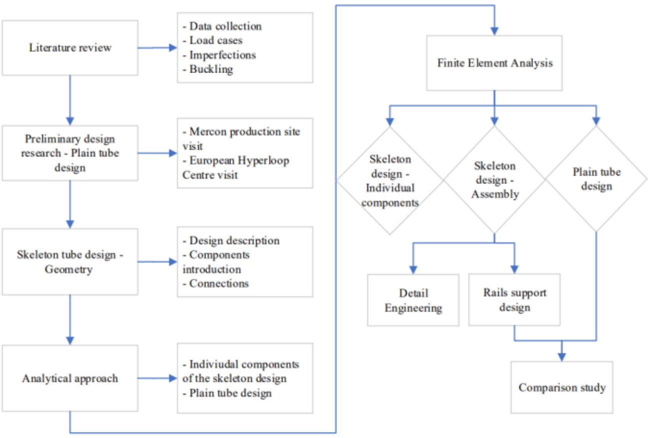

Figure 1: Workflow diagram

3 Modelling and Results

Some of the hyperloop infrastructure concerns are passenger safety, financing, maintenance costs, government regulations, and due to the potential length of the hyperloop infrastructure, it also has a significant environmental impact. Therefore, new lightweight designs are being constantly developed and researched. The components of this design are presented in *Figure 2*.

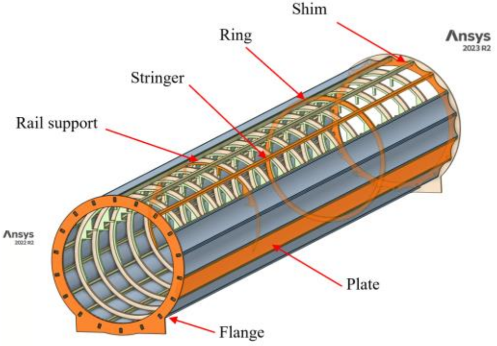

Figure 2: Components of the Skeleton tube design

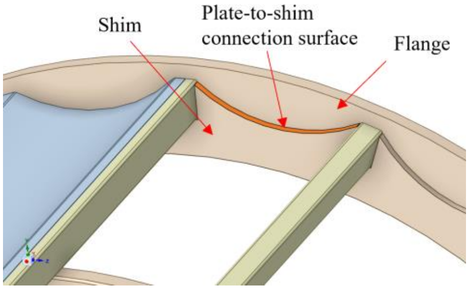

Figure 3: Shim and flange detail

The hyperloop system does not have unified rules for the infrastructure design yet. Thus, recent reports do not consider the same load cases or load magnitudes. In this research, seven known load cases were considered, also presented in Table 1.

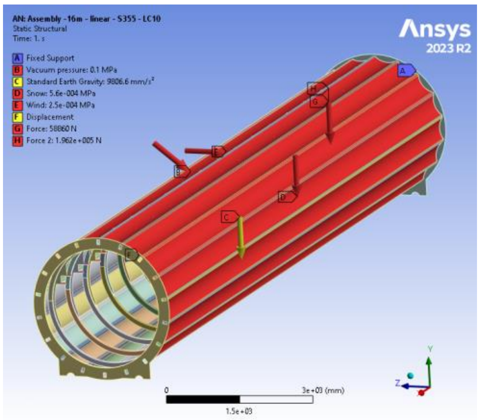

Figure 4: Setup of the assembly in Ansys software [1].

Load case	**Load magnitude**
q_{self} - Self-weight	/
q_{vac} - Vacuum pressure	0.1 MPa
q_r - Rails load	58.860 kN
q_w - Wind load	0.375 kN/m^2
q_s - Snow load	0.56 kN/m^2
$q_{s.pod}$ - Static pod load	196.2 kN
q_{br} - Breaking of the pod	3.06 kN

Table 1: Load cases and load magnitudes

Two assembly models were analysed: i) a true scale 16m long model for the global vertical deflection verification, and ii) a 5m long model for ULS verification, local deformations and eigenvalue buckling analysis. Three most probable load combinations were considered; these are also indicated in *Figure 6*. Those combinations are as follows:

LC1: Vacuum pressure only: $1.2q_{self} + 1.2\psi_0 q_{vac.} + 1.2\psi_0 q_r$
LC2: Snow: $1.2q_{self} + 1.2\psi_0 q_{vac} + 1.2\psi_0 q_r + 1.5\psi_0 q_s$
LC10: Critical combination: $1.2q_{self} + 1.2\psi_0 q_{vac} + 1.2\psi_0 q_r + 1.5\psi_0 q_w + 1.5\psi_0 q_s + 1.5\psi_0 q_{st.p.}$

The strength evaluation of the model resulted in the maximum von Mises stress of 342.56MPa at t = 2.2s. This translates to UC = 0.96; therefore, the structure still exhibits an elastic response.

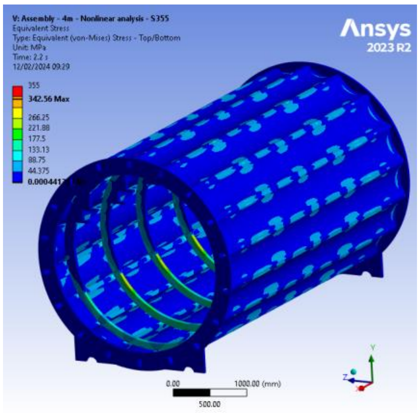

Figure 5: Von Mises stress [MPa] for S355 model

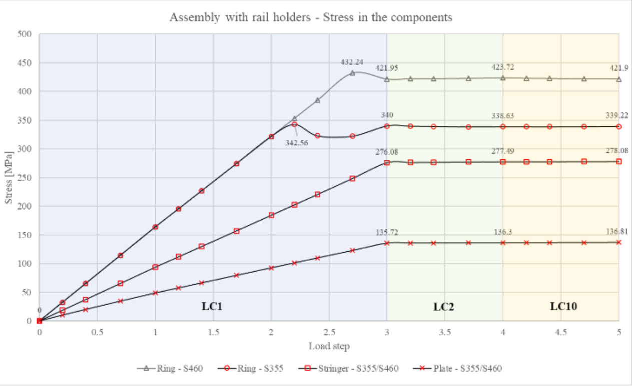

Figure 6: Maximum Stress [MPa] versus Time step [s] for critical components. The time steps indicate load combinations.

Observing the ring stress curve, the peak is at t = 2.2s. After this point, the stress decreases. This is because a plastic response was triggered. This initiation of plastic deformation caused the ring to deform locally and distribute the concentrated stresses.

The buckling resistance of the tube was assessed through a nonlinear analysis, where the initial imperfections, residual stresses and material non-linearity are taken into account [2]. The yield strength is reached at vacuum pressure of 0.082MPa (*Figure 8*), then a plastic plateau is seen from p = 0.143MPa until failure at p = 0.17MPa.

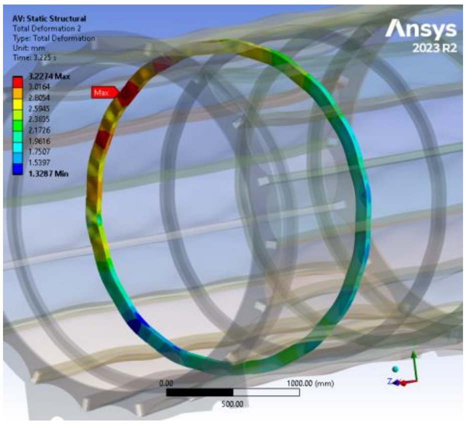

Figure 7: Scaled-up deformation [mm] of the buckled ring at the failure point for visualisation

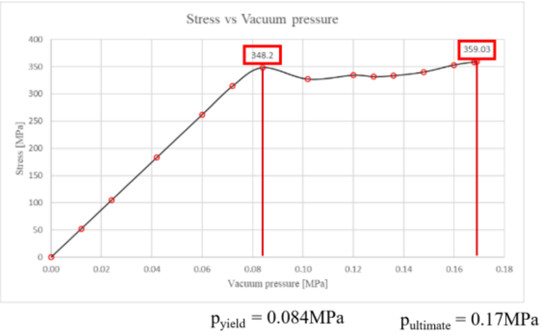

Figure 8: Stress [MPa] vs vacuum pressure [MPa] of the buckled ring.

One of the critical points in the design is the connection between the stringer and the ring. Therefore, a bolted steel bracket connection has been designed. The goal of this design is to mitigate stress concentration and prevent local yielding. Additionally, to ease the installation process and improve maintenance and the component replacement process in case of failure.

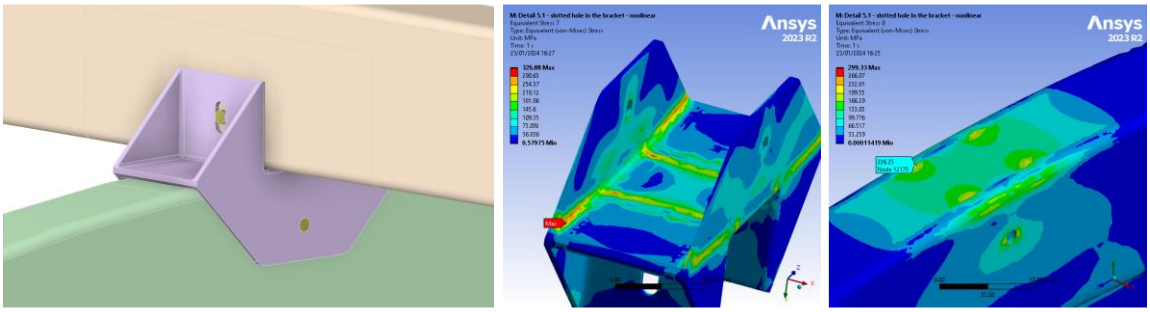

Figure 9: Starting from the left: Steel bracket connection; Stress [MPa] in the bracket; Stress [MPa] at the ring contact surface.

The maximum stress in the ring at the contact surface resulted in 226MPa, while the maximum stress in the bracket resulted in 326MPa. Local deformation of the ring, stringer and bracket were all within acceptable limits.

Lastly, the plain tube design has been modelled and analysed. The plain tube is currently used at the European Hyperloop Center [3], and it serves as a benchmark design in this research.

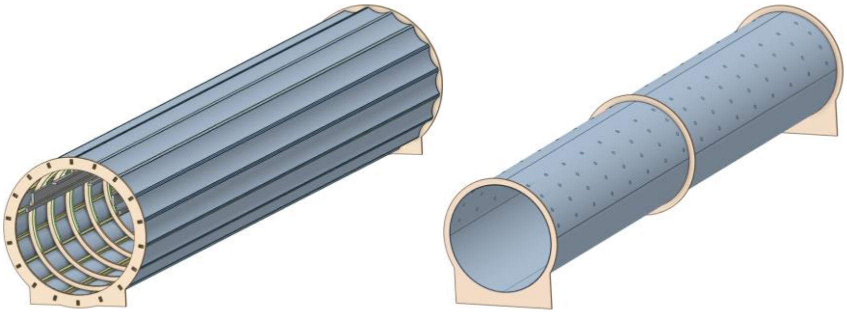

Figure 10:Skeleton tube design and Plain tube design modelled in Ansys software [1].

Both tubes were compared in eight different aspects and the summary is presented in Table 2.

	ULS	**SLS**	**Stability**	**Impact load**	**Thermal expansion**	**Sustainability**	**Production**	**Maintenance**
Plain tube design	++	++	+	++	-	--	o	+
Skeleton tube design	-	o	+	--	+	++	-	o

Table 2: Summary of a comparison study between the plain tube design and skeleton tube design

4 Conclusions

The aim of this research is to provide a preliminary analysis and a foundation for further research on skeleton hyperloop tube design. The design was not only structurally verified but also modified and optimised for better structural and operational performance. The following conclusions were made based on the obtained results:

1. ULS is conditionally satisfactory with the unity check of 0.96. Nonlinear response initiates locally in the rings, but the assembly nonetheless exhibits an elastic response.
2. The structure has an insufficient capacity to bear any additional loads.
3. Rails support is designed to be fully fixed to the rings. Therefore, they act as a reinforcement of the assembly and improve its structural performance.
4. A global vertical deflection of 3.34mm satisfies the deflection limit.
5. Local deformations of components are within the limits.
6. The skeleton tube has no resistance to accidental loads and/or impact loads due to its slender design.
7. Steel bracket design reduced maximum stress at the ring-to-stringer connection from 342MPa to 226MPa.
8. Skeleton tube design outperforms the plain tube design in the sustainability aspect, but it underperforms in terms of ULS, SLS and impact load.

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