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Analysis of a spatial flexible frame for the scenography of a dance performance using a geometrically exact rod model

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Abstract

As a central piece of the scenography for a contemporary dance solo–performance, a flexible spatial frame has been designed. The structure consists of several straight steel tubes, rigidly connected, forming a single poligonal line *winding round* in space: a central horizontal member, located 2.5 m above stage level, allows for suspension of the artist; this bar is joined at every end to stirrup–shaped members (with two inclined and one horizontal parts), each one clamped at only one end on a rectangular basis frame. The whole structure is asymmetrical, with ca. 3.5 m span and a maximum height of about 4 m. Moderately large displacements and rotations are expected. This behaviour is assumed to fit into the so called *geometrically exact rod model*, first proposed by Reissner and Simo [5]. FE analysis based on this theory has been developed by several authors (Simo & Vu–Quoc [6] and Ibrahimbegović & Taylor [1], among others). We carry the design of our structure taking into account the results of a static nonlinear analysis with a self developed Reissner–Simo finite element model [2].

1 Introduction

For the purpose of a contemporary dance solo performance, a flexible frame has been designed as a central piece of the scenography. The choreography has been created with the *leit–motiv* of this structure which acts as spatial reference and also as a tool from which the dancer, suspended upside down, performs several movements during about 8 minutes. The concept of the structure has been developed by the scenographer under the idea of a very light and slender rod which plots a path in the space parting upwards at one side, winding round in the center and coming down to the ground at the other side; the central part of this path forms a kind of loop which should allow for the suspension of the dancer. Other requirements, as lightness (limited weight), easy assembly (and disassembly) and transportability should be considered. From the structural viewpoint several questions had to be solved to meet the aesthetic and functional requirements. A slender, and therefore flexible frame should be designed. The idea of a winding rod led immediately to the consideration of tubular cross-sections in order to resist the twist in the three–dimensional structure. The use of aluminium instead of steel could have been a reasonable choice for the sake of lightness, but was discarded considering the allowable budget. Some difficulties had to be solved concerning joint design, support–basis design, stability and vibration control. Project deadlines and scale let no possibility to develop a detailed analysis of dynamic-response, therefore the design has been based on a static nonlinear analysis checking the necessary safety.

2 Description of the structure

The structure can be divided in two parts: the basis frame and the spatial frame. The basis is a 3.30 m side square–shaped frame. It is made up of rectangular 80 × 60 × 4 mm S275 steel tubes. The two opposite corners are specially designed as rigid joints for the lower members of the spatial frame. The spatial structure is asymmetrical. It consists of several straight steel tubes, rigidly connected, forming a single poligonal line *winding round* in space. Every steel tube has a 60×4 mm circular cross section. The supporting members are clamped on the corners of the basis leaving ca. 4.7 m span. The left support tube reaches 4 m height and the right one stops at 3.5 m. Two horizontal members, parallel to each other, are joined to the upper ends of the support members; they are continued with two inclined members and the whole frame is closed by a central horizontal 1 m long member, located 2.5 m above stage level, allowing for the suspension of the artist. For easy disassembly, the spatial frame is divided in 4 L-shaped and one U-shaped parts. Four 12 mm screws and an inner welded tube allow for a rigid union in each joint. The base frame can be disassembled in 4 L-shaped and 2 straight pieces with the same kind of joints.

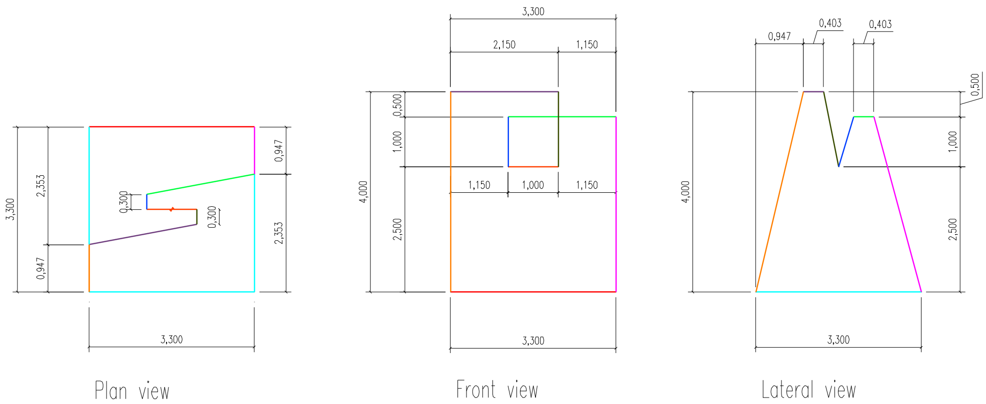

Figure 1: 2D view

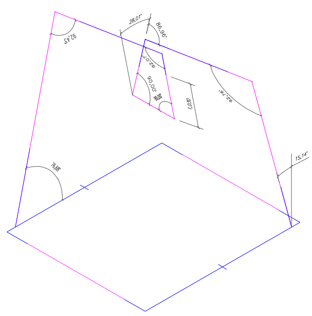

Figure 2: 3D view

3 Analysis

A preliminary stage of the analysis comprises the evaluation of the non-linear behaviour of the structure. For this purpose two structural models have been analyzed: a linear FE model and a geometrically non–linear FE model formulated on the basis of the Reissner–Simo beam theory. The latter has been developed (with some changes from reported implementations) by the authors; details can be found in [2]. Both models comprise only the space frame clamped on a rigid basis. The non–linear model is made up of 42 two-noded Reissner–Simo linear elements with one point reduced integration. For this comparison self–weight has been neglected and a dancer's weight of 0.667 kN has been considered. Two (static) design gravity loads on joints 21 and 23 (of the central rod) modeling the dancer's weight (0.5 kN in each joint corresponding to a security factor $\gamma_F = 1.5$), and two horizontal forces due to inertial effects (0.25 kN in each joint perpendicular to the span) have been set. A load control strategy was considered up to 20 times the reported joint forces. Equilibrium paths are shown in figure 3. Up to a load factor of 4 the behaviour is nearly linear. Higher loads cause a sensible drift from the linear response.

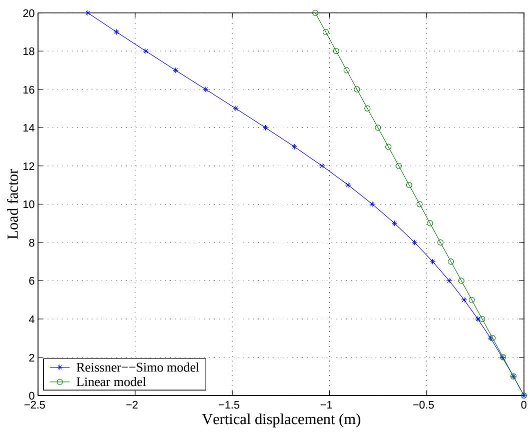

Figure 3: Linear vs. non–linear response. Vertical displacement of central joint

In order to validate the cross-sectional design, the evolution of section forces during the load process has been analyzed. Element 24, located on the shortest inclined member next to the horizontal central member, suffers the highest section forces and moments. Figure 4 shows the performance ratio considering interaction between torsion, bending and axial forces. The 60 × 4 tubular section behaves properly up to a load factor of 3. For this load factor (corresponding to 6 times the dancer's weight) the vertical displacement amounts 0.22m, and the stored deformation energy has a value $U = 0.48382$ m kN. The stored energy equals the value of the potential energy of the 0.667 kN dancer at a heigth of 0.73 m, and therefore would be equivalent to the impact of the dancer falling from about 0.5 m. This result shows how the design reaches a good safety requirement, due to the fact that the dancer's movements will not reach such remarkable limits.

4 Conclusions

A spatial flexible frame for a dance performance has been designed to meet the aesthetic, functional and safety requirements. A useful tool for the design has beer a non–linear Reissner–Simo FE model, allowing to evaluate the importance of the non–linear response. Design was based on a static analysis, but led to consideration of the deformation energy to estimate a reasonable limit of the artist's movements.

5 Acknowledgements

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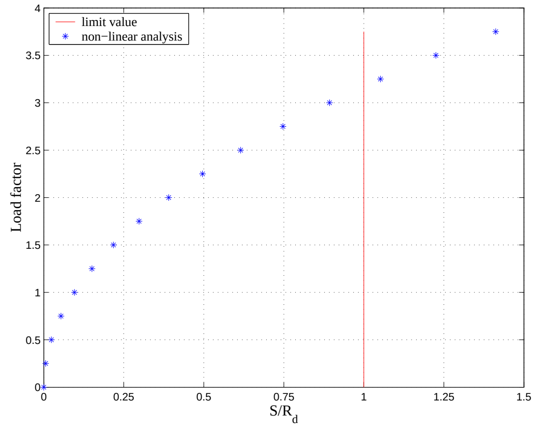

Figure 4: Performance ratio for element no. 24

Figure 5: Central part detail

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