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Development of a procedure for the structural design of roller coaster structures: The rails

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A R T I C L E I N F O

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A B S T R A C T

In this paper a procedure for the design of the structures of a generic roller coaster (*RC*) is described. This activity is part of a partnership that the authors are entertaining with one of the major European amusement park industries. The full procedure, developed on theoretical bases and under simplified hypotheses, aims to make designers able to properly and quickly size the complete structure (for complete structure authors mean rails and support structures). In the present paper the design of the rails is presented. The data, needed by this procedure, are the rail track tridimensional geometry and the time histories of contact forces between vehicles and rails. The procedure has been subsequently verified by applying it to an existing *RC* in order to test all its capabilities and foresee future development and improvement, aiming to insert it in a consolidated general procedure, ever growing and expanding.

1. Introduction

The activities of this paper fits inside of a research agreement signed between the *Department of Engineering* of the *University of Perugia* (Italy) and *Antonio Zamperla S.p.A.* (Italian company dedicated to the design, construction and installation of amusement park, rides and equipment) [1–3]. Within the procedure thus far developed, aimed at the design of roller coasters (*RC*), the present activity has set the goal to analyze issues of dimensioning and verification of the structures, that is rails and supporting structures (Fig. 1).

In the paper, a design procedure, developed on a theoretical basis, is described. Although not without simplifying assumptions, it wants to fully respond to the need of the designer to quickly but also properly size all the structures, structures that are then adequately verified by a series of numerical structural calculations (i.e. by using the finite element approach – *FEA* [4,5]). The database of this procedure are the three-dimensional rail track geometry and the interaction forces between the rail and the vehicles. The development of the rail track geometry is conducted in a computer aided design (*CAD*) environment developed by the authors [1,2] inside a commercial *CAD* software [3], also with the help of simplified numerical dynamic simulation tools, made with the numerical language (*VBasic*) supported by the software itself. The interaction forces are instead obtained by a modeling and simulation multibody tool, designed and built for the aforementioned activities [3]. These are however obtainable by whatever dynamic simulation tool or software as time histories [6,7].

The hypothesis on which the present work is based is that the design of the structures can be divided into two logical steps: the sizing of the *rail structure* and the sizing of the *supporting structure*. To take into account the mutual interaction of the two substructures from the start of the design is quite expensive and, therefore, the choice of splitting the design of the structures into two steps was necessary. Consequence of this hypothesis was, however, the additional choice of a series of successive hypotheses that, in order not to lose information, make the design process at least as safe as the standard one.

The design of the track is carried out by adopting a theoretical model of the *continues beam* (*rectilinear beam*) on more supports, loaded by a train of loads. The hypothesis of perfect constraints maximizes the action of the constraints themselves and, therefore, the stress condition on the rail structure. The loads of each wheels are exportable from *MBS* code and post processed by ad hoc developed routine, in order to make them available as a function both of the time and of the curvilinear abscissa of each track, of the *project line* (the ideal designed trajectory of a point mass) and of the *center line* (the middle line defined by left and right track) [8]. The same are further available in the global (*absolute*) coordinate system of the structure as well as in a local reference frame, the so-called *kinematic plane*(tangent, normal and binormal directions), function of abscissa location, as defined in [9–11]. The whole is simplified if

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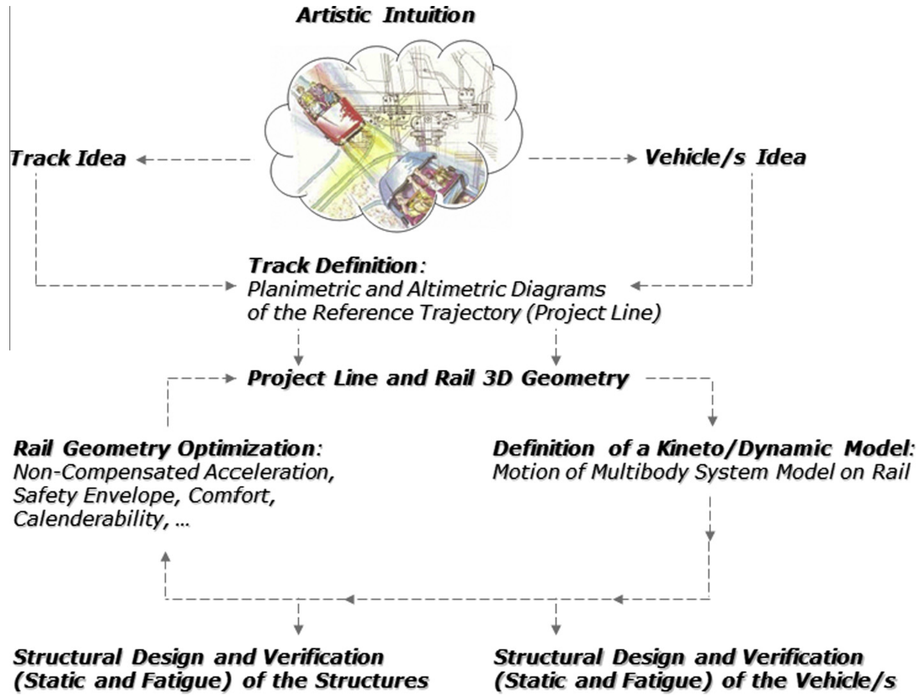

Fig. 1. Flow chart of the design process through the developed general procedure.

to be analyzed are the resultant loads of each axle of the vehicles train of the multibody model.

The developed dimensioning procedure, therefore, allows to determine the allowable geometric characteristics of the rail having as control parameters the allowable stress and deformation (displacement) assigned as design data.

The entire procedure was then used to analyze an existing Zamperla *RC* in order to test its capabilities, as well as to improve and optimize it, in order to permanently incorporate it in the general procedure (Fig. 1) ever growing and expanding.

2. The design of the rail structure

The design of the track is conducted by adopting the hypothesis (*hp.*) that the *rail structure*, simple or complex, can still be modeled as an equivalent beam, continues, on more, evenly distributed, supports (*hp. 1*) and that the load condition is represented by the loads resultants of every axles (*hp. 2*), representing the cars train of the multibody model. The assumption of perfect constraints (*hp. 3*) maximizes the action of the constraints and, therefore, the stress on the rail structure. The design is addressed by using the normal and binormal components (local reference system of the *kinematic plane)*of the load resultant of the generic axle.

Even if this should be the theoretical procedure, experience has confirmed that the rail dimensioning can only be carried out by considering the loads normal component (*hp. 4*). The transverse loads (binormal component) determine, in fact, second order load conditions onto the track and mainly affect the sizing of the supporting structures.

The track curvature, in general, does not involve substantial changes in stress distribution in the idealized section of the equivalent beam nor in the real rail structure. This, combined with the need to simplify the dimensioning step, determines the additional hypothesis to consider the rail as straight (*hp. 5*) and then to adopt a plane scheme both for the structure model and for the load condition.

The load condition, i.e. the values to be taken for the resultants set, evaluable by multibody analysis in every instant of the simulation, is a further choice that the designer must do.

The resultants set are obtained and choose by several dynamic simulations that consider a lot of load (passengers) condition (worst case analysis).

The procedure allows to apply any loads distribution, positioned as from kinematic model (i.e. distribution assumed by the resultants normal components in the instant in which one of these assumes the maximum value of the entire simulation, distribution of the resultants normal components equal to the maximum value that any of these assumes in the entire simulation).

The procedure automatically defines a number of spans of the beam model, as a function of the total number of axles and of the train longitudinal dimension, so as to obtain a distribution of the internal loads that does not be affected by the boundary conditions.

The analysis of the stress state and, therefore, the identification of the train most critical location, as well as of the section with the maximum stress condition, was carried out by using and developing the definition of *influence line* [12–15].

The developed dimensioning procedure allows to determine the allowable geometrical characteristics of the track, expressed in terms of area (A), moment of inertia (J) and section modulus (W) of the equivalent beam, as well as the maximum allowable span length (L), by having as control parameters stress and deformation (displacement) allowable condition, assigned as design data. The rail is linked to the definition of beam by structural equivalence biunivocal relations that are function of the rail structure type (i.e. 2/3 tubes rail, 3/4 tubes reticular rail); these relations are simple for simple types and somewhat complicated and conditioned by particular existence limits in the case of types more complicated. These last have needed, in special conditions, a numerical validation by finite elements approach [5]. All these relations, then, allow to relate macro parameters J and W to the effective geometry of the rail structure.