The roller coaster
A design challenge combining excitement and rigour

by Livio Furlan
EnginSoft

A roller coaster can be considered as a metaphor for life, with its ascents and descents characterizing life's ups and downs, evoking deep emotions from fears to be overcome to joys to share. It is probably for this reason that it is difficult to imagine an amusement park without immediately thinking of a roller coaster as the symbolic attraction, evocative of a desire to feel truly alive, to force oneself out of one's comfort zone, and to change the trajectories of one's daily routine, striving for experiences that fill one's days with life.

Historical background
What is the origin of the roller coaster, so emblematic of an amusement park?

Amusement parks date back to the medieval fairs scattered across Europe in the early Middle Ages. The word "fair" is derived from the Latin word "feria" used to describe the religious festivities that were celebrated during the Roman Empire. Similarly, in the early Middle Ages, villages organized fairs in the grounds adjacent to the local church or abbey for the feast of their patron saint.

Edward I of England, however, banned what he considered to be a desecration of the churchyard, forcing fairs to be held in other public areas such as town squares. Thus fairs evolved from being festivals to celebrate patron saints to becoming popular attractions and meeting places for local communities. Over time, they also became recreational, commercial and tourist attractions, evolving into today's amusement parks.

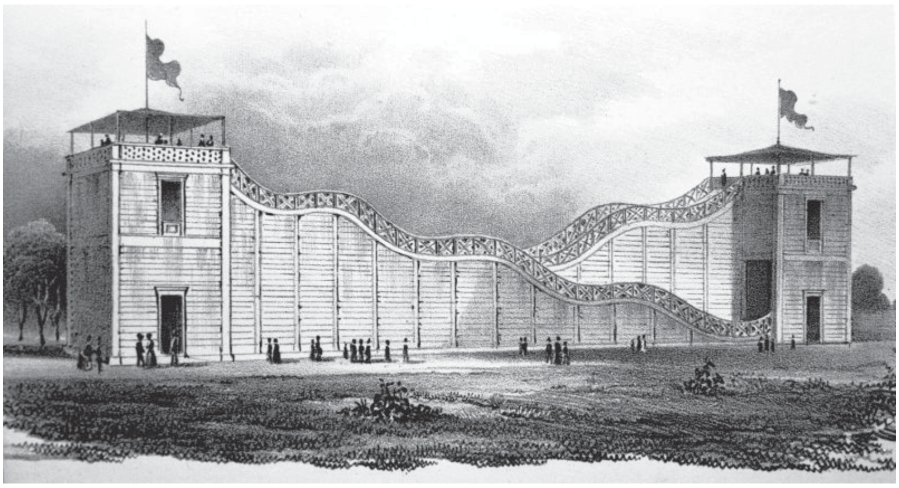
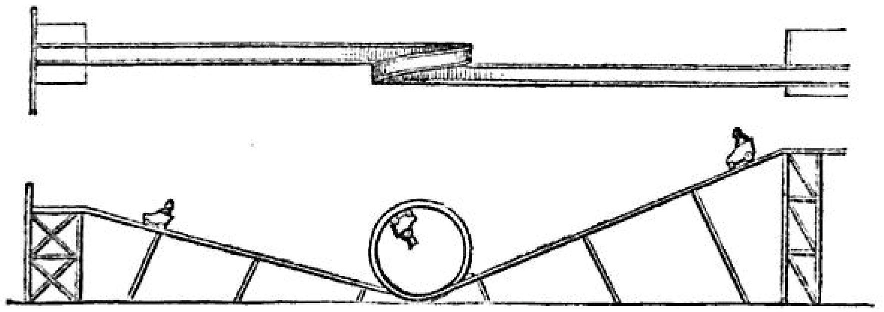
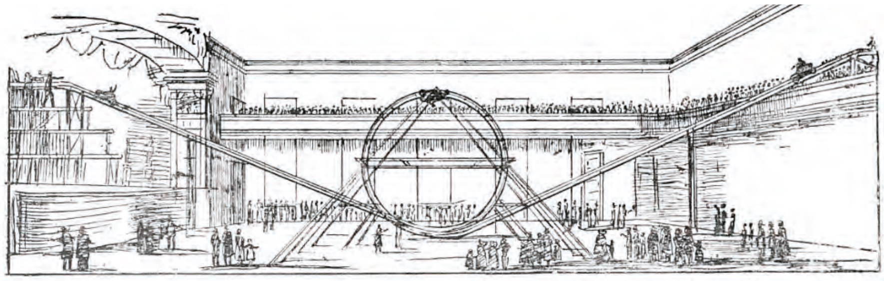


Fig. 1. The first roller coaster in Tivoli Gardens in Copenhagen, Denmark. Public domain, via Wikimedia Commons.



Simple design diagram of a centrifugal railway from the 1840s. Hutchinson, Higgins, et al. Public domain, via Wikimedia Commons.



A detailed sketch of a Centrifugal Railway in Manchester. Illustration unknown, published in work by Powys-land Club. Public domain, via Wikimedia Commons.

Fig. 2. Centrifugal railway.

As fairs spread across Europe as far as Siberia and eastern Russia (despite the harsh climatic and environmental conditions), they became important commercial gatherings. From the 16th century onwards, Russian cities near rivers – in particular, St. Petersburg with its Neva River – built numerous “ice slides” or “flying mountains” that became pseudo-permanent attractions thanks to the cold temperatures.

The “Russian Mountains” purposely built around St. Petersburg in the 17th century as part of its winter festivals, featured 20-25-metre-high wooden structures with wooden stairs that led up to the 180-metre-long ice slides with slopes steeper than 100% (the angle of the slide was about 50 degrees relative to the horizontal). Users would ride down the ice-covered wooden slides on sledges made of hollow blocks of ice filled with straw at first and later made of wicker. The slides were sprayed with water daily to keep the ice slippery while sand was sprinkled along the bottom of the slide to slow the descent, allowing the users to climb the ladder up to the next slide to continue the fun of “flying down”.

Tsarina Catherine II, a great fan of the thrills provided by the slides, commissioned a pair to entertain herself and her courtiers at her palace in Oranienbaum on the Gulf of Finland, and had wheels added to the carts and grooved rails added to the slides to create a summer version of the “flying mountains”.

But who created the first “real” roller coaster using carriages with wheels? Some historians credit the Russians with building the first machine on wheels but during Napoleon's invasion of Russia in 1812, the French discovered this form of entertainment, brought the idea back home, and significantly developed it. They built two roller coasters in Paris in 1812, known respectively as "Les Montagues Russes” at Belleville with tracks and carts on wheels with axles, and "Promenades Aeriennes” or the Aerial Walk which had two opposing curved tracks that met at the base of the attraction where a climbing system brought the carts back to the top for the next ride to take place.

In the wake of the Napoleonic wars and the wave of nationalism spreading across Europe, the French began to organize national exhibitions, culminating in the French Industrial Exposition of 1844 in Paris. This fair was followed by other national exhibitions in the Old Continent, participation in which was facilitated (and enabled) by the technological advances at the height of the Industrial Revolution that led to the construction of navigable waterways, railways and steamships. Exhibitions resemble medieval fairs in their ability to attract people from faraway places and, like medieval fairs, these increasingly international exhibitions attracted trade and soon began to showcase and promote the technical-scientific achievements of nations.

In was here that the entertainment attractions provided for the participants of the exhibitions also witnessed innovation which today would be defined as Research and Development. Hence, the first example of a centrifugal railway (Fig. 2) i.e. a looping roller coaster, came into being. This attraction was installed in 1845 at Frascati Gardens in Le Havre and consisted of a track descending from a height of 43 feet (13m), a loop of 13 feet (4m) in diameter, and an ascending section to enable the rider’s cart to stop. The attraction operated for 20 seasons but went out of fashion and was closed following an accident that claimed one life.

Although there were many labour injustices during the Industrial Revolution, industrialization generally freed millions of people from subsistence farming and created more leisure time for the average population. In particular, many Americans began working fewer hours and had more disposable income.

As a result, the roller coaster, progeny of the Russian Mountains, was no longer a monopoly of the ruling classes and began to be built everywhere. America, specifically, had an abundance of land to build large rides, the engineering know-how to create ever more innovative roller coasters to meet the demand of a growing population of thrill-seekers, and the forests to provide the construction material: wood, which was used to manufacture roller coasters from the second half of the 19th century until the first half of the 20th century.

LaMarcus Thompson, often considered the “Father of the Roller Coasters” and the “Father of the Gravity Rides”, emerged in the States of the Union of that time. He is credited with the conception and construction of "Coney's Switchback Railway" in Coney Island in New York in 1884. This structure features a tower from which passengers board a large cart with bench seats. Like a roller coaster, the trolley descends a 600-foot-long (183m) ramp to another tower, travelling at approximately 10kph. At the top of the second tower, the cart is moved onto a second track to allow it to return to the first tower.

Roller coasters in the short century

In the wake of Coney's Switchback Railway's popularity, others "designed" and built bigger and faster rides. Shortly afterwards, Charles Alcoke developed the first attraction with a complete oval circuit, also made of wood, called the Serpentine Railway. Although steel was already widely used in the construction industry, especially in the railway sector, its debut in roller coaster production only dates back to 1959, when the Disneyland theme park introduced a new twist in roller coaster design with the Matterhorn Bobsled. This was the first roller coaster with a track made of tubular steel parts.

Unlike traditional wooden tracks, tubular steel tracks can be curved in any direction, allowing designers to incorporate inversions into their designs. This is why many modern roller coasters are made of steel, although a few wooden ones are still being built to satisfy the fans of this type of coaster.

The years from 1970 to 1990 saw the construction of the largest number of roller coasters since the 1920s. Anton Schwarzkopf (a German roller coaster designer) and F.lli Pinfari (an Italian roller coaster manufacturer) pioneered the use of tubular steel tracks. They ushered in a new era of roller coasters, adopting the Loop feature and introducing the first attempts at new and even more exciting shapes such as the Corkscrew, the Immelmann Turn, the Dive Loop, the Cobra Roll, etc. It was on the basis of these shapes that a new revolution in the design and construction of roller coasters took place between the 1990s and 2000s in order to increase excitement levels:

- **1992**: the first Inverted Coaster was introduced; this is a roller coaster in which the train runs suspended from the tracks and the seats are connected directly to the wheel bogies;
- **1996**: the first Coaster to use the LIM (Linear Induction Motor) propulsion system which "shoots" the cars to the top of the first climb without the need for traditional lifting systems which are made with chain and sprockets (chain lift) or with special wheels equipped with tyres (boosters);
- **1997**: the first Flying Coaster. This type of rollercoaster is designed to simulate the sensations of flight and keeps passengers in a prone position for the duration of the ride. Like Inverted Coasters, the carriages are suspended below the track with passengers' bodies positioned parallel to the track itself;
- **1998**: the first Dive Coaster. This type of steel roller coaster gives passengers a moment of free fall with a drop of at least 90 degrees (Oblivion, Alton Towers);
- **1999**: the first Floorless Coaster. In this version of a steel roller coaster, passengers sit inside a floorless car and their feet swing just above the track.

Safety matches emotion

As may be expected, partly due to the construction possibilities afforded by the evolution in production technologies, the use of steel as the main manufacturing material, and increased understanding in context of phenomena that formerly lacked clear explanation (fatigue behaviour, for example), the limits of ride performance research have been – and are still being – pushed forward every day. The ensuing challenges, safety first and foremost, are therefore significant and decisive and leave no margin for error in evaluating

the mechanical-structural behaviour of these complex systems in response to stressful dynamic actions. Therefore, the only way to fully “understand” this type of structure and to design the structural components and mechanical parts of the entire carousel properly and safely is to use virtual prototyping with associated numerical simulations.

Given the complexity of a roller coaster project, especially one with above-average performance, numerical simulations must obviously be combined with the requisite technical skills in order to provide enthusiasts with increasingly exciting products, as well as to integrate the various stages of design of the track and the vehicle/train that travels it, with an eye to comfort and the requirements/limits of acceleration imposed by sector standards.

A numerical approach to roller coasters design

Accordingly, the different aspects of roller coaster design clearly require specific, integrated, and interconnected development phases. Beginning with the customer's requirements, these phases move from feasibility to execution and use virtual prototyping tools (CAD-CAE-FEM) that not only guarantee the precision and safety of the final product, but also offer unbeatable advantages in terms of cost control.

The added value of virtual prototyping is also evident in the quantity and quality of information obtained, which influences the designer’s ability to overcome engineering challenges without sacrificing competitiveness and business objectives.

Furthermore, the customization of calculation and verification tools (calculation procedures) in a virtual testing environment accelerates the conception and design phases, reduces errors, and enables the acquisition of skills that can be used in subsequent processes/projects.

It is safe to say that comprehensive and advanced simulation tools, complemented by specific knowledge, are key to investigating the mechanical-structural phenomena typical of roller coasters and achieving ever higher design standards and reliability levels.

The specific, integrated, and interconnected development phases outlined above are summarized below.

Step/Phase 1 – Client requests

In this first phase, the following aspects are considered depending on the type of roller coaster being designed/built:

- Customer ideas and/or requirements;
- Track ideas (children, families, thrill factor…);
- Vehicle/car ideas (standard, spinning, inverted, etc.);
- Boundary and constraint conditions by location: flat terrain, hillside, open area, shopping centre, etc.

Step/Phase 2 – Initial proposals (architectural evaluation)

Considering the customer's requests and, therefore, the type and level of thrill desired for the attraction, initial drawings are developed to share ideas leading to the final design. The activities therefore involve:

- Issuing multiple layouts based on the customer’s idea;
- Producing 2D drawings (plans, elevations) for an initial assessment-evaluation;
- Generating the first renderings with simplified 3D of the roller coaster in the right environment (including video);
- Defining the preliminary ride performance data (based on experience).

Step/Phase 3 – Layout based on dynamic response

Once the preliminary track layout has been defined, the first dynamic calculations necessary to identify where to insert the appropriate transition curves and to define the track elevation values to make the curve transitions more comfortable are developed:

- Modifying the 2D drawings (plan and elevation) with the introduction of transition curves;
- Generating the 3D spline (centreline) and introducing spatial figures (Loop, Immelmann, Corkscrew);
- Preliminary ride dynamics (point masses);
- First track banking evaluation and preliminary safety checks.

Step/Phase 4 – Interactive optimization process

This is the main optimization process and is based on recursive steps, with a full multibody analysis performed as a final check on accelerations once the track geometry has been locked:

- 2D/3D layout modification;
- Simplified dynamics (point masses);
- Tracking of banking evaluations;
- Verification of environmental constraints (safety envelope);
- Full multibody analysis;
- Acceleration assessment and data verification, for example, with respect to the requirements of EN 13814 (see Fig. 4).

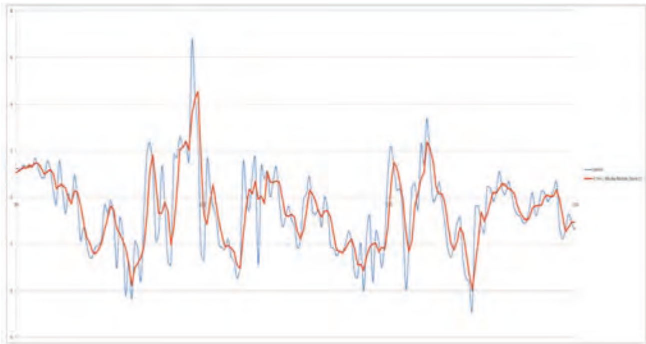


Fig. 3. Example of a comparison between real acceleration and calculated acceleration.

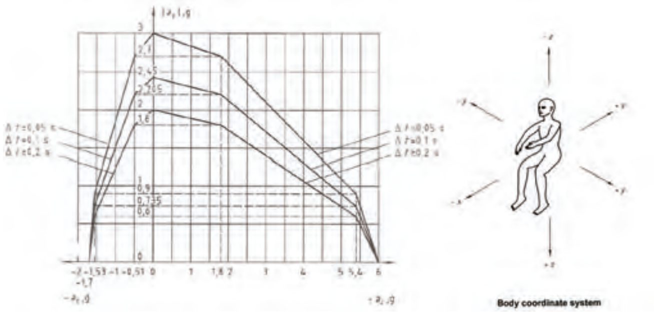


Fig. 4. Domain within which the accelerations a_y and a_z must lie (from the requirements of EN 13814).

Comparing the results (accelerations) of virtual prototyping (multibody models) with accelerometric data obtained from tests over the years on their corresponding real-world tracks provides the certainty that numerical simulations, when conducted with the appropriate experience and expertise concerning physical phenomena, are reliable and provide consistent data upon which to develop the roller coaster design.

This means that the project becomes more robust and secure as it develops on the basis of validated mathematical models. After all, innovation, a field that rightly includes roller coasters, requires flexibility; flexibility requires abstraction (as in concepts and theory); and the language of abstraction is mathematics. However, mathematics is more than language: it can be used to deepen knowledge, to search for optimal solutions, and to design efficient algorithms based on the mathematical equations (algebraic, functional, differential, and integral) that support the physics of systems.

Together, technological innovation and mathematics can form a virtuous interaction process to generate a reliable representation of the mechanical-structural behaviour of roller coasters and their components.

Step/Phase 5a – 2D/3D model of the roller coaster attraction

After dynamic optimization, the roller coaster structures, and car frames/components can be modelled in detail to prepare the final drawings/documentation for construction and delivery:

- Generating the 3D primary model of the full ride containing columns, rails, base frame, station, etc.;
- Issuing the 2D workshop drawings with all details (materials, welding procedures, NDT tests, etc.);
- Drawings for tube bending and track construction (3D coordinates and jigs);
- Manuals (operational, inspection), and risk assessment documents.

Step/Phase 5b – Roller coaster structural models

Based on the 3D master models and the dynamic multibody model, the following activities are conducted for the final calculation phase of the overall attraction.

- Postprocessing of accelerations related to the vehicle system which are provided both by automatic calculation (based on the physical-mathematical relationships in industry standards) and by dynamic multibody model, also for comparative purposes;
- Evaluating the forces on the carriage wheels (load-bearing wheels, guide wheels, side wheels) for each load case associated with the curvilinear co-ordinate of the train's progress along the track;

Fig. 5. Finite element model of a roller coaster.

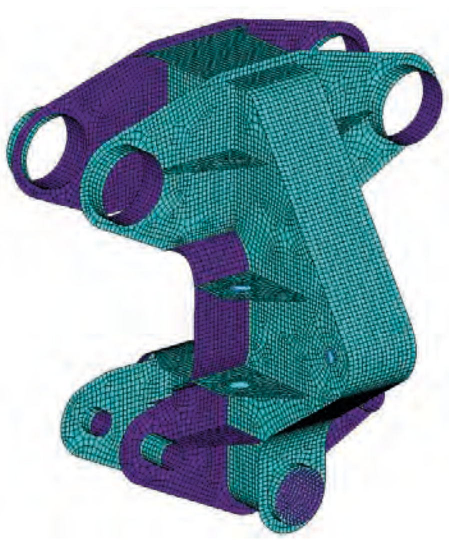


Fig. 6. Finite element model of a car bogie.

- Creating a 3D beam+shell finite element model with properties and group assignments to comply with the automatic strength and fatigue check procedure;
- Exporting a TXT file containing all data concerning the roller coaster structure to perform the FEM analysis (see Fig. 5);
- Performing linear/non-linear structural analyses considering both the environmental actions (if any) and the forces transferred from the carriage to the track;
- Performing code verifications in terms of strength and fatigue testing of the structural elements, welded connections/joints, and bolted connections/joints.

Step/Phase 6a – 2D/3D carriage model

Depending on the type of car/train (standard, spinning, inverted, etc.) the design of the structural and mechanical parts and their theme is developed. These activities include:

- Transforming ideas into first sketches (mechanical, structural, and theming solutions);
- Transforming preliminary 2D drawings into 3D models (including the fibreglass bodies forming the scenic part of the train);
- Creating the detail design of the car bogies, axles, and frames;
- Defining the mechanical connections between the structural parts, and designing the electrical plan, and all ancillary parts of the cars/train.

Step/Phase 6b – Mechanical-structural calculations/models of the carriage

Once car design is complete, the numerical models and verification calculations (mainly fatigue calculations) of the various components are developed:

- Creating a 3D beam+shell finite element model of the bogies (see Fig. 6) and the car frame;
- Performing linear/non-linear structural analyses considering the accelerations experienced by the cars/train during a full lap of the ride;
- Conducting normative checks regarding the strength and fatigue testing of the bogies (see Fig. 8), structural elements, pivots, axles, connecting bars, welded connections/joints, and bolted connections/joints;
- Performing optimization activities involving/reducing the mass of the carriages/main components of the train (reducing the train's masses reduces the forces acting on the carriages and consequently on the track).

The final point above is a key activity, and involves phases 5b, 6a and 6b. These optimizations (which actually reduce the masses themselves) can be achieving by working on two levels: firstly by containing/decreasing the weights by modifying the component geometries, and secondly by introducing lighter materials than steel (such as austempered cast irons, or aluminium alloys).
The second level, due to its use of "modellable" materials, enables substantial redesign of the parts and components of the cars and results in the creation of a "lightning train", i.e. the convoy's reduced mass allows it to traverse the track in a more restrained manner requiring less energy to be launched and slowed along the route and reaching higher speeds (or greater heights) than an equivalent "traditional train" with the same amount of energy applied at launch.

The regulatory framework

This integrated numerical approach incorporates the regulatory requirements both for the calculation of the dynamic actions affecting the track and the cars/train, and for the development of the verifications to calculate the minimum safety margins necessary to achieve compliance. Some of the standards are listed below:

- ASTM F2291-23: Standard Practice for Amusement Ride Design;
- EN 13814: Fairground and Amusement Park Machinery and Structures;
- EN 1993-1-9: Design of Steel Structures – Fatigue;
- IIW - Recommendations for Fatigue Design of Welded Joints and Components (for Hot Spot Stress approach);
- UNI 7670: Mechanisms for lifting devices – Instructions for the calculation (considered for the calculations/verifications of non-welded components).

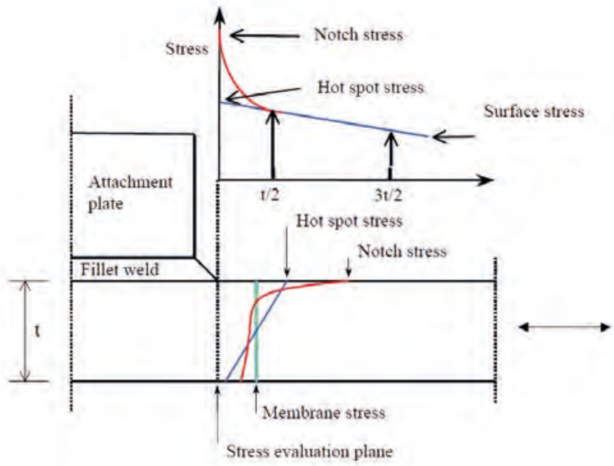


Fig. 7. Schematic stress distribution at a hot spot (taken from the Recommended Practice DNV RP-C-203).

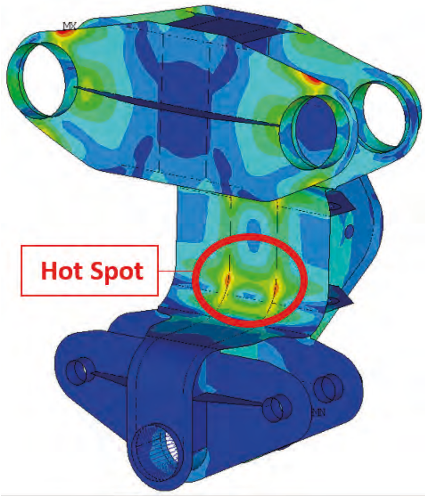


Fig. 8. Bogie region to be verified by hot spot method.

Regulatory verifications are conducted for strength resistance and buckling resistance as well as fatigue response (fatigue resistance) checks. As previously mentioned, for roller coasters (and all rides in general) the phenomenon of fatigue on metallic materials, associated with the cyclic nature of actions and stresses, is decisive and sizable.

Therefore, an extensive check is necessary for each area and, particularly, for regions with stress concentrations that may trigger problems resulting in possible failure.

Fatigue damage calculations use appropriate calculation methods (e.g. the rainflow counting algorithm) at each significant point based on the stress history (derived from each lap) and define the number of cycles in a specific stress range ($\Delta\sigma_i$) as well as the value of accumulated damage, using appropriate S/N curves and the Palmgren-Miner rule.

Detailed FEM analyses of the complex welded construction parts, whether in roller coaster structures, bogies and/or car frames, may be necessary to reliably determine stress concentrations. However, even with the aid of finite-element analyses, it can be difficult to assess which "nominal stress" should be used for the S/N curves, since part of the local stress from a specific detail type is already taken into account in the S/N curve for that very type of detail.

Sometimes, it may prove more convenient to use an alternative approach (the so-called hot spot method) to calculate fatigue damage when local stresses are obtained from the finite element analyses and when notch stresses are difficult to assess due to the significant dispersion in the local weld geometry and different types of imperfections. The numerical procedure for the hot spot method is based on two assumptions:

- the notch stress factor that results from the welding is included in the S/N curve to be used (as specifically defined by the standards concerning the calculation of fatigue damage); this S/N curve can usually be considered as the hot spot S/N curve;
- stress concentration caused by the geometric effect of the actual detail is calculated by using a shell or solid finite element model with a suitably fine mesh to obtain a reliable value for the SCF (stress concentration factor) which increases the nominal stress.

Since the notch effect of the weld is included in the S/N curve, the stress at the hot spot is derived by extrapolating the structural stress at the base of the weld as exemplified in Fig. 7. Note that the strain used as the basis for this extrapolation must be external to that affected by the weld notch but close enough to detect the effects of local geometry.

Drag reduction – CFD's contribution

Enthusiasts' search for greater thrills has driven designers and manufacturers to creating roller coasters with progressively longer tracks, more figures/inversions along the tracks, and taller structures for the trains

of cars to scale. LIM propulsion systems allow trains to be propelled at higher initial speeds, due to the greater efficiency of the launch systems.

The speeds and thrill factor are augmented by increasing the cross-sectional dimensions (more passengers per row) and the number of cars and, therefore, the load capacity, i.e. the number of passengers per run. As the transversal and longitudinal dimensions of trainsets grow, evaluating aerodynamic actions, i.e. the interactions between the air and the solid body of the train as it moves forward, becomes important. In fact, during the lap, the initial kinetic energy (of launch by LIM or, in traditional lifting systems, generated by the first descent) is gradually lost due to friction and air resistance.

It is precisely the latter that can influence the speed of the train/carriage and, therefore, the length of the ride. If one underestimates the kinetic (or potential) energy that the train must have at the start of a turn, the train risks coming to a standstill on a gradient before it can descend and continue along the track. It therefore follows that it becomes important to foresee the dissipation of kinetic energy caused by drag in certain situations.

Since wind velocity increases with altitude, wind forces opposing the train's motion can be particularly significant on taller roller coasters, also relative to their interaction with the speed of the train. Aerodynamic studies therefore play an essential role in the design simulation of modern, extreme roller coasters in order to cater for the high speeds and the forces opposing the train's progress along the track.

Furthermore, drag can increase substantially on the winding parts of high-speed routes when the carriages (2-4 seats) of the same train fan out, widening the frontal area of the entire train that is exposed to the wind. Computational fluid dynamics (CFD) can play an essential role in the design of modern roller coasters to accommodate high-speed resistance (and wind-induced actions).

To obtain indications of the effect of passengers on the drag coefficients, numerical analyses use models of the train with (occupied seats) and without (empty seats) passengers. The geometry of the entire train is generated by copying the surface geometry of a single car/carriage (with and without passengers), as many times as the number of cars in the train.

The train's overall geometry is placed in a sufficiently large air domain to ensure that the sensitive results are not affected by edge effects. Numerical steady-state simulations are performed on the domain, which is divided into polyhedral cells, using the k-ε turbulence model for different apparent wind speeds and directions. The aerodynamic coefficients (drag coefficient in particular) are calculated from the CFD analysis results, which are used to define the drag resistances.

The benefit of CFD simulation lies in the possibility of redesigning seat and fibreglass shapes as deemed appropriate to significantly improve performance, without having to conduct real experiments. In other words, CFD simulations enable an in-depth understanding of the aerodynamic behaviour of the trains, giving designers new inspiration to develop progressively more exciting roller coasters.

For more information:

Livio Furlan - EnginSoft
l.furlan@enginsoft.com