Preliminary analyses for the study of the effects of an explosive action on a long-span suspension bridge

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Abstract

Terrorist attacks have nowadays become an important issue for the structural design of constructions such as bridges. Indeed, during the last decades, the increase in the number of terrorist attacks has resulted in the loss of many human lives and socio-economic impact on our society. The aims of this research consist in a series of preliminary analyses in view of a study of the effects of an explosion on a long-span suspension bridge. As a suspension bridge was considered the project of the bridge over the Strait of Messina, having as main span of 3300 meters. The structure was modeled using ABAQUS/Explicit software using beams-type 3D finite element modeling. The objectives of the research are double. The first one is the study of the pressures generated by an explosive charge to model the phenomenon during numerical simulations while, the second objective, is to test different discretizations to have a reliable numerical response.

Keywords: long-span suspension bridges; blast loading; mesh-size problem; fast dynamic; numerical simulations.

1 Introduction

Suspension bridges are the longest-span structures of any type. Typically, this type of structure consists of two piers, two main cables passing through the top of the towers and anchored to large foundations at the ends of the structure, as well as the deck, which is suspended along its entire length from the main cables by multiple suspension hangers. Throughout history, technical and scientific advances have made it possible to build ever larger suspension bridges. The first of them was the "Jacob's Creek Bridge" built in 1801 in Pennsylvania in the United States with a span not exceeding 21 meters. Since then, the engineers of the last two centuries have been constantly improving the original concept, materials, and calculation methods. Today, the records of span easily exceed the one and a half kilometers and the maximum span ever built reaches almost two kilometers with the famous Akashi Kaikyõ Bridge of Japan that crosses the

Seto Inland Sea linking the cities of Kobe and Awaji.

These structures must be able to resist various loads such as their own weight, variable loads such as traffic due to road traffic, the passage of a train or the action of wind or ground movements. However, certain events or combinations of accidental events have already led to progressive collapses of this type of structure. Since the construction of the first suspension bridge in the early 19th century, several collapses have already occurred. For example, the famous Tacoma Narrows Bridge in the United States collapsed (1940) due to a resonance phenomenon on the structure caused by the wind [1]. Another quite famous collapse is that of the "Silver Bridge", a suspension bridge in Ohio, which collapse occurred in 2001, due to a slight defect in a main cable which, over the years, has worsened due to corrosion and fatigue phenomena, until it broke [2]. As another example of failure, we also note the "Kutai Kartanegara Suspension Bridge". In November 2011, during the maintenance of one of the suspension lines, it broke, causing the death of a dozen workers [3].

These collapses are all due to unintentional causes (lack of knowledge or human error). Unfortunately, in recent times, engineers must also consider a collapse load that depends on human will: the terrorist attack.

In 1996, the Irish Republican Army (IRA) missed a bomb attack on Hammersmith Bridge in London. Two 30-pound semtex bombs were installed under the bridge deck. This amount of explosive could have led to a complete failure of the bridge. Two months later, an even larger attack was carried out in the center of Manchester with a 1500 kg mass placed in a vehicle. More recently in 2016, two simultaneous terrorist bombings took place in Belgium, in Brussels, respectively in the Maelbeek metro station and in the main terminal of the national airport of Zaventem. In these attacks 35 people lost their lives. Earlier, in 2014, a similar act by the Boko Haram Islamist group had already killed 21 people in the Nigerian capital. Many other examples of bomb attacks can be cited, such as the Oklahoma attack on government buildings in 1995 or the 1998 the 1998 attacks on the US embassies in Kenya and Tanzania.

Explosive incidents occur either accidentally or intentionally. But in either case, they are unpredictable and can result in serious injury, death, and heavy structural damage. They also have a severe impact on people's minds and the economy. As for bridges, they are essential components in the transportation infrastructure, they take part in the popularity of certain locations and also symbolize the link between cities, countries and cultures of our societies. These costly structures are therefore attractive targets for any terroristic attack.

Therefore, it seems evident the interest of engineers and researchers to perform numerical simulations that can provide knowledge regarding the safety and structural robustness of this type of structures when subjected to a blast load. However, the modeling and numerical analyses that must be performed are quite complex and onerous in terms of computational effort, since they are numerical analyses in fast dynamics with different types of nonlinearities (at least geometric and material).

This research paper aims to study a particular aspect of numerical analysis which in scientific literature is called mesh-size problem [4, 5, 6]. To obtain an accurate solution, since blast loading is an action that occurs in fast dynamics, the discretization must be much finer than the discretization that can be used for static loads or slow dynamic loads (earthquake or wind). For this reason, given the computational effort of any numerical analysis, it may be interesting to perform some case studies that consider only parts of the structure to be analyzed to focus attention on the quality of the numerical response.

In the next paragraphs, the structure of the reference suspension bridge will be briefly described, some reminders on blast modeling will be exposed and two case studies will be proposed to define an efficient discretization for hangars and deck beams for when nonlinear analysis in fast dynamics is required.

2 The long-span suspension bridge considered

The long-span suspension bridge considered in this research is the project of the Messina Strait Bridge.

An image of the structure is reproduced in Figure 1A. As can be seen, the structural scheme of the bridge has a single span, with a distance between towers of 3300 meters.

The 52 m wide deck consists of three box girders joined by transverse girders every 30 m. The central box girder is the passage way for two railway lines while the lateral box girders have three road lanes on each girder (Figure 1b). At the side of the road lanes there is a lane dedicated to the maintenance of the bridge. The suspension system has two pairs of main cables positioned at the sides of the deck. These four cables possess a diameter of 1.24 m.

The deck is joined to the main cables by a system of hangers placed at a distance of 30 m from each other. The towers are 382 m high structures composed of two longitudinal elements slightly inclined towards the axis of the bridge and four transverse elements. Each leg has a section that can be inscribed in a rectangle of about 12 x 16 m while the crossbeam section is 4 x 16.9 m. Further details about the materials used in the project and the geometries of the sections can be found in the following papers in scientific literature [7, 8, 9, 10].

3 The blast modeling

3.1 Mathematical formulation

In the literature [11, 12], the evolution of the pressure wave over time, caused by an explosion, is generally described by the Friedlander equation:

$$P_S(t) = P_{S0} \times \left(1 - \frac{t - T_a}{T_0} \right) \times e^{\left(-b \times \frac{t - T_a}{T_0} \right)} \tag{1}$$

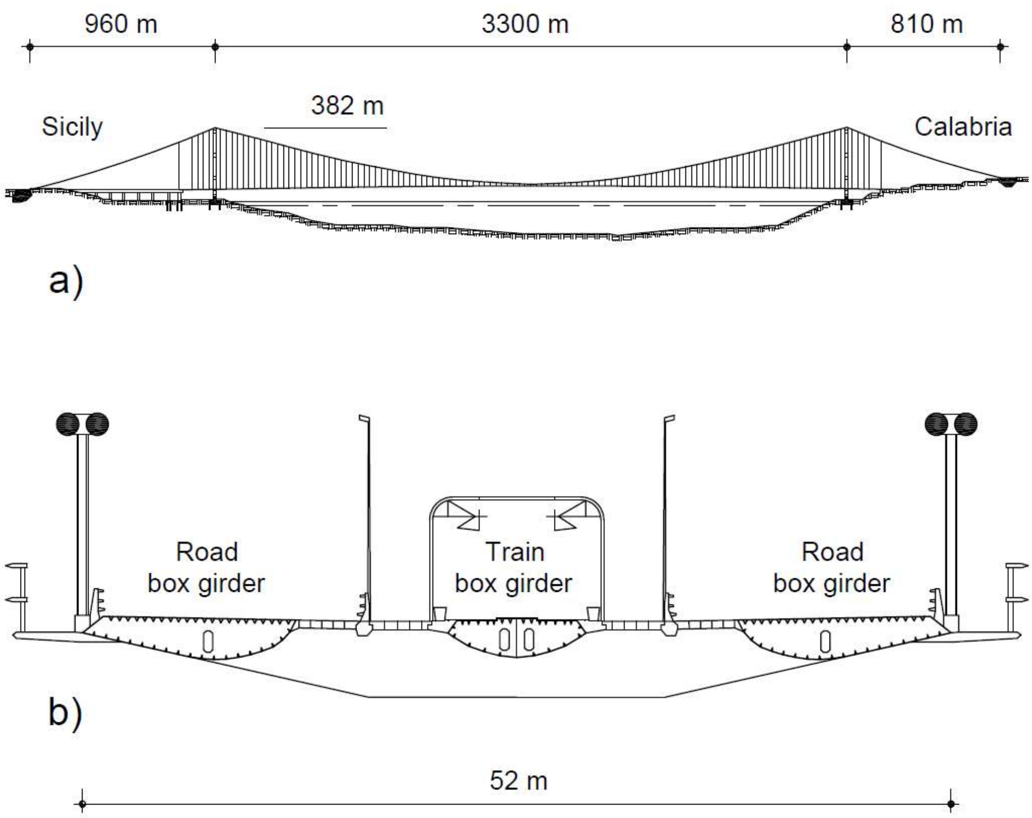

Figure 1. General view of the project of the suspension bridge over the strait of Messina

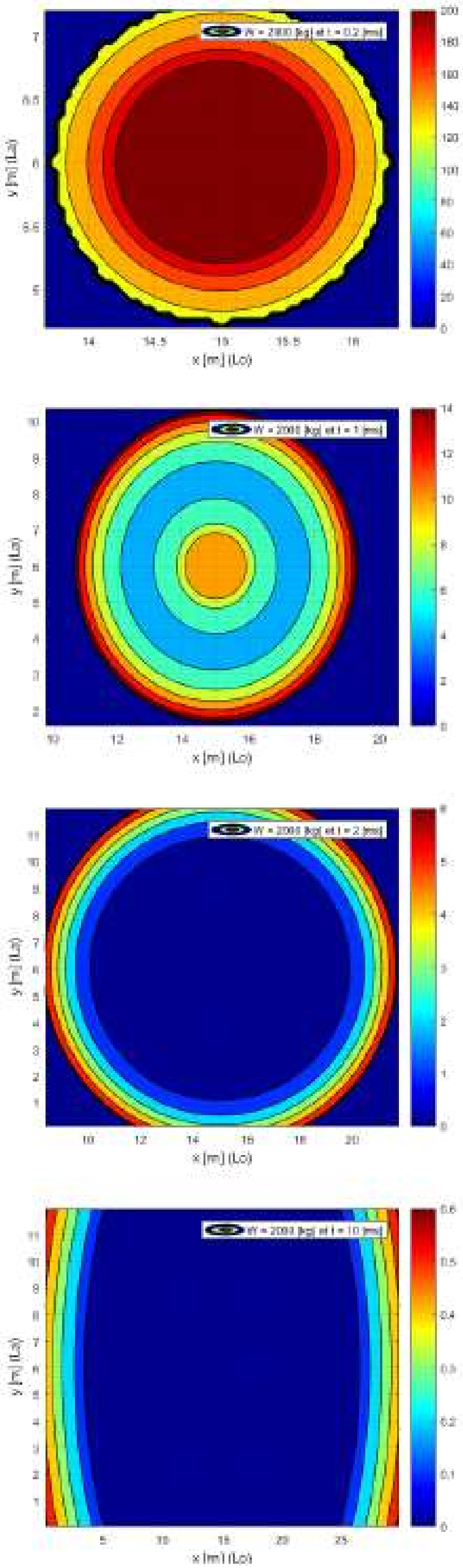

Figure 2. Time evolution of the blast pressure on an area of 12 x 30 m

where the coefficient b is the coefficient of degrowth of the wavefront and depends on the environment and the distance from the center of the explosion. To evaluate this parameter we used the formula proposed in Karlos et al. [11] :

$$b = -22.35 + 569.23 \cdot Z - 3657.05 \cdot Z^2 + 11895.32 \cdot Z^3 - 22101.20 \cdot Z^4 + 23778.69 \cdot Z^5 - 13737.89 \cdot Z^6 + 3283.57 \cdot Z^7 \quad (2)$$

if the Z value is between 0.15 and 1 and :

$$b = 0.20 + 13.77 \cdot \left[\frac{0.55}{1 + \exp\left(\frac{Z - 1.13}{0.18}\right)} + \frac{1 - 0.55}{1 + \exp\left(\frac{Z - 1.04}{1.83}\right)} \right] \quad (3)$$

if the Z value is between 1 and 40. Z is the scaled distance that depends on the distance R from the explosion and on the explosive load W according to the equation:

$$Z = \frac{R}{\sqrt[3]{W}} \quad (4)$$

The other parameters present in Eq. (1) are P_{S0} (maximum pressure), T_a (arrival time), T_0 (positive duration) and, in general, they depend on the position of the analyzed point, its distance R from the point to the center of the explosion and the amount of explosive W involved (Kingery and Bulmash [12]). In this research, a simplified versions of the Kingery and Bulmash model proposed by Jeon et al. [13] were used, in which all these parameters can be described by the equation:

$$Y = 10^{C_0 + C_1 \cdot \log(Z) + C_2 \cdot \log(Z)^2 + C_3 \cdot \log(Z)^3 + C_4 \cdot \log(Z)^4} \quad (5)$$

Constants C_0, C_1, C_2, C_3, and C_4 depend on the scaled distance Z and their values can be found in the publication of Jeon et al. [13].

3.2 Bridge deck pressure evaluation

Through the formulae exposed in paragraph 3.1 it is possible to evaluate the over-pressures generated on the surface of the deck by the explosion load, which will be then inserted as a load in the numerical model. Figures 2 shows the pressure front diagram at a given instant during the first 10 ms after the explosion for a TNT load of 2000 kg. The diagram qualitatively shows the advancement of the pressure wavefront over an area of 12 m (width of bridge deck beam) x30 m (distance between hangers).

These diagrams were numerically integrated over the area of the bridge deck to obtain the second diagram in Figure 3 representing the time variation of the resultant explosion force.

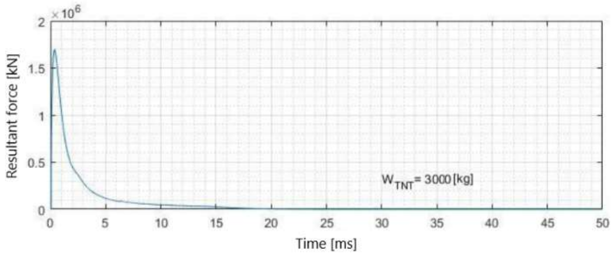

Figure 3. Integrating process of the pressures derived from the explosion load

4 Mesh size analysis

In this paragraph we examine the two case studies developed on the basis of the geometry and mechanical characteristics of the Messina Strait Bridge to define the discretization to be used for the hangers and deck beams in the study of the effects of an explosion on the structure. These models are not intended as simplified "equivalent" models but only as case studies "similar" to the complete structure. The use of such case studies, instead of the complete structure, was necessary due to the high computational effort required to solve every single dynamic analysis.

Case studies were developed using ABAQUS / EXPLICIT, an environment created to simulate brief transient dynamic events where the response of the structure is sought by integrating the dynamic equilibrium equations through an explicit solution algorithm (central difference algorithm). The explicit procedure integrates over time by using many small-time increments but is only conditionally stable and the stability limit for the operator (with no damping) is given in terms of the highest frequency of the system as:

$$\Delta T = \frac{2}{\omega_{\max}} \tag{6}$$

To avoid numerical instability problems, the automatic time stepping option was used during the analyses. In this case ABAQUS/EXPLICIT independently chooses the time step increment based either on the maximum frequency of each finite element (conservative choice) or on the maximum global frequency [14, 15].

4.1 First case study

The first case study was geared towards finding the correct discretization of hangers. In general, in numerical models having the goal of investigating the behavior of the bridge under static or slow dynamic loads, each hanger is discretized with only one finite element. This discretization is highly inadequate for investigating the waves of stress that propagate along the cable at the moments of the explosion.

Therefore, the first case study represents the modeling of a hanger performed with beam-type linear finite elements. Figure 4 shows the geometry and mechanical characteristics of the modeled hanger. The geometries and mechanical properties shown in Figure belong to the bridge described in Section 2 and considered for this research.

The upper end was assumed to be fixed, while, at the lower end, the mass can move only in vertical direction. In terms of masses, in addition to the density of the cable, a mass of approximately 230 tons was placed at the lower end. This "equivalent" mass was identified to have a static tension of about 170 N/mm^2 (stress value present in the hangers caused by the weight of the bridge structure) [9, 10, 15]. The time history describing the explosion load equivalent to a TNT mass of 3000 kg was also placed at the lower end.

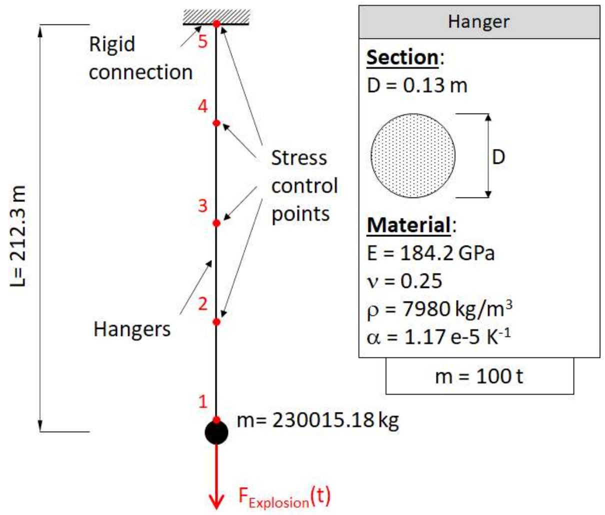

Figure 4. Geometry and mechanical characteristics of the case study analyzed to identify the appropriate level of hanger discretization

The structure in Figure 4 was studied by performing 4 different discretizations. In the first, the cable was modeled with 4 finite elements of equal length, in the second with 40, in the third with 400 and finally with 4000. Displacements and stresses were checked at the 4 control points shown in the figure.

From the comparison of the graphs in Figure 5 we can see that the discretization with 400 finite elements and that with 4000 finite elements provided substantially coincident results. Assuming as a result of comparison the one related to the discretization with 4000 finite elements (which led to a size of the finite element along the cable of 5.3 cm), we can say that the discretization with 40 finite elements generated values of stress and displacement reduced on average by 25% while the discretization with 4 finite elements led to values reduced by 80% (in addition to providing a response qualitatively much poorer).

On the basis of these results, in the next paragraph, a discretization equal to 400 finite elements will be assumed for the hangers closest to the explosion load.

Furthermore, as can be seen in the stress graph in Figure 5, the use of a discretization suitable for the analysis of a static load in the case of a fast dynamic simulation, can lead to underestimate by 4 times the tension in the cables.

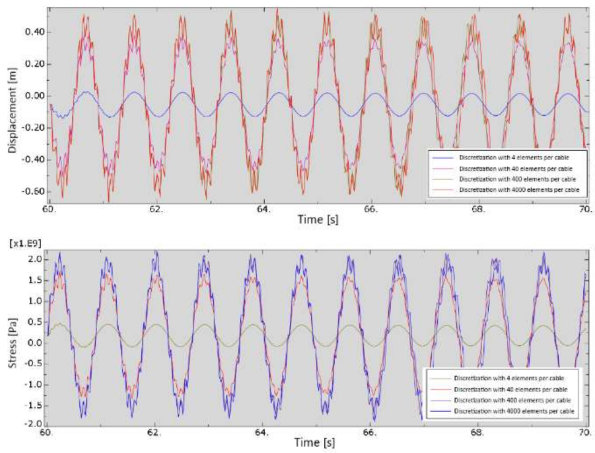

Figure 5. Temporal variation of the vertical displacement and of the stress state at the stress control point 1 for the four discretizations analyzed.

4.2 Second case study

The second case study was analyzed with the aim of understanding the influence of the discretization of deck beams in the evaluation of the cable stress state. For this analysis, the static scheme reproduced in Figure 6 was examined. Once more the authors point out that this static scheme was not intended to be an "equivalent" or "simplified" scheme for the study of the propagation of an explosion effect in the bridge but only a structure on which to perform preliminary analyses and define a correct discretization of the elements.

In this case study it was planned to use 3 cables having the same geometry as the cable studied in the previous paragraph, spaced 30 m apart. The three upper ends were considered fixed while the three lower ends were joined by a beam having the same characteristics as a bridge road box girder of the bridge described in Section 2. Vertical slide and an elastic restraint were placed on either side of the beam to reduce displacements under blast loading. The stiffness of this constraint was set, arbitrarily, using the $3EI/L^3$ formula and the geometric and mechanical parameters of the road box girder [9, 10]. An explosion load equivalent to a TNT mass of 3000 kg was placed at the right end of the beam.

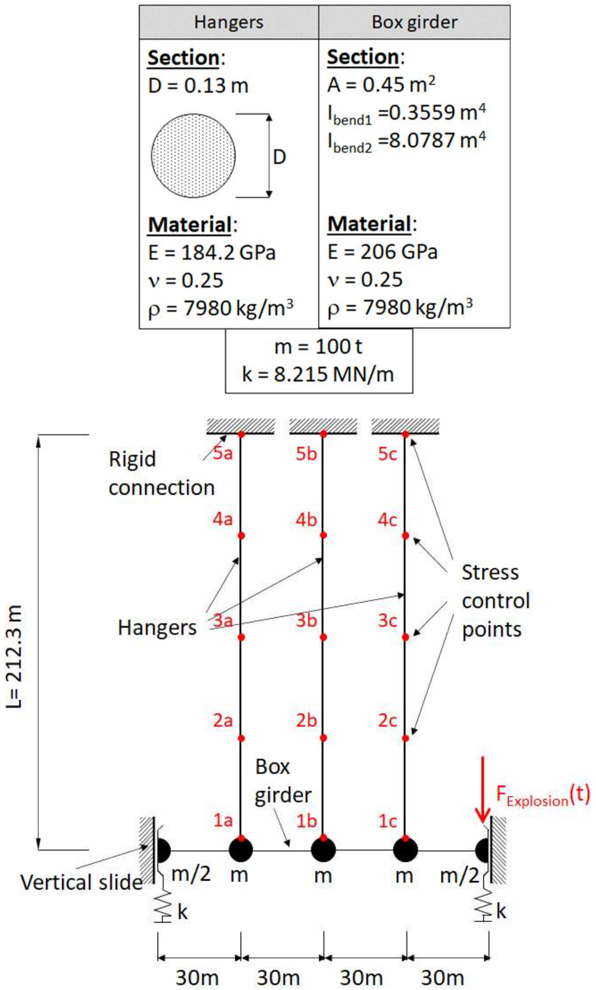

Figure 6. Geometry and mechanical characteristics of the case study analyzed to identify the appropriate level of beam discretization

The structure in Figure 6 was studied by performing 4 different discretizations. In each model, the cable discretization was always defined with 400 finite elements, based on the previous case study. In the four models performed, a discretization for the road box girder of 1, 10, 100 and 500 finite elements was considered. Displacements and stresses were checked at the 4 control points shown in the figure.

Figure 7 shows the results obtained at the stress control points 1a (Figure 6). Comparison of the graphs in Figure 7 showed that the discretizations with 100 finite elements and of that with 500 finite elements provided substantially coincident results. Assuming as a result of comparison the one related to the discretization with 500 finite elements (which led to a size of the finite element along the beam of 6 cm), we could see that the discretization with 10 finite elements generates errors on average of 10% on the displacement values while the discretization with 1 finite element led to errors on average of 30% on the displacements.

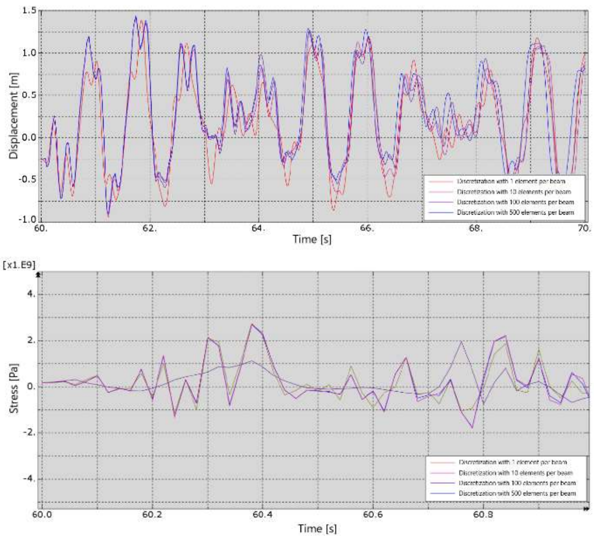

Figure 7. Temporal variation of the vertical displacement and of the stress state at the stress control point 1a (Figure 6) for the four discretizations analyzed

On the stresses in the hangers, the difference in response was more marked, both qualitatively and quantitatively. The discretization with 1 finite element, which provided a qualitatively very poor response, led to errors of 90% while the discretization with 10 finite elements led to the evaluation of stress values with an error of 50%.

5 Conclusions

This work focuses its attention on the problem of mesh size definition in fast dynamic simulations designed to simulate an explosion load on a large span suspension bridge.

The paper illustrates two case studies, used to define the dimensions of beams type finite elements within a 3D modeling of the structure. The first case study focuses on the definition of the mesh necessary to have a good response in terms of displacement and stress, in the hangers, the second case study examines the analogous problem for the beams that compose the bridge deck.

The analyses carried out show that to obtain a good numerical response there is necessary to use beams elements of about 50 cm in length for the cable (which easily leads to have 400 finite elements for each cable of the global model) and 30 cm for the bridge deck beams.

The use of inadequate meshing, e.g., based on numerical models for solving static or slow dynamic problems, leads to underestimates of up to 400% in the evaluation of stress in cables.

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