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DYNAMIC ANALYSIS WITH DAMPING FOR FREE STANDING STRUCTURES USING MECHANICAL EVENT SIMULATION

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În acest articol se prezintă o metodă modernă, care consideră amortizarea, pentru proiectarea şi optimizarea structurilor energetice aeriene expuse solicitărilor dinamice.

Procedura de proiectare prezentată în acest articol implică unul dintre cele mai moderne concepte de simulare numerică – Mechanical Event Simulation – în investigarea, analiza şi optimizarea geometriilor complexe care sunt de obicei zonele critice pentru structurile energetice aeriene.

Metodologia de proiectare expuse în acest articol plasează structura investigată în direct contact cu mediul înconjurător iar încărcările se vor calcula automat pe baza acestei interacţiuni.

Utilizând această metodă, inginerul proiectant, nu va mai fi nevoit să aproximeze încărcările şi să le aplice într-un mod static. Interacţiunea structura-mediu înconjurător va fi simulată realistic astfel încât vor fi excitate sursele care generează oboseala zonelor critice ale structurii şi anume încărcările ciclice.

This Paper presents a modern, new approach, which accounts for damping, in designing free standing structures that are subject to dynamic induced loads.

The procedure outlined in this paper involves the most advanced engineering simulation concept – Mechanical Event Simulation – to investigate, analyze, and optimize very complex geometries that are usually the most critical areas for free standing structures.

The new design approach proposed in this paper places the system in direct contact with the surrounding environment and calculates the loads based on this interaction.

Using this method the engineer no longer has to approximate the loads and to apply them statically. The simulated interaction will be a realistic one triggering the fatigue sources which are the cyclic loads.

Keywords: Dynamic Analysis, Damping, Numerical Simulation, Free Standing Structures

Introduction

One of the most amazing achievements in engineering is the practical application of Numerical Simulation.

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Leibnitz's dream [1], almost three centuries ago, of developing a generally applicable method that could arrive at a solution to a differential equation of any type became possible in our time with revolutionary discoveries in the computer and computing domains.

Practically, numerical simulation has been applied successfully for more than 50 years in the main engineering disciplines.

Today, the market offers a large variety of general purpose numerical simulation software, which in the hands of a well trained engineer can become an extremely powerful engineering tool.

The latest developments in computing technology have made it possible to simulate the world around us, as it really is … in a nonlinear fashion.

The Mechanical Event Simulation (MES) [2] concept introduced and developed by ALGOR Inc.[1] represents a paradigm shift in engineering design. It allows engineers and designers to simulate the actual conditions that a mechanical component will experience; that is, the event associated with its application.

This is possible because MES accounts for both the interaction of the component with its surroundings, and the inertial forces generated by the motion of the component itself.

To simulate the nonlinear behavior of the (surrounding) real world one of the most critical parameters the analyst must account for is the damping coefficient.

Characterization of damping forces in a vibrating structure has long been an active area of research in structural dynamics. In spite of significant research, thorough understanding of damping mechanism is not well developed. A major reason for this is the state variables that govern damping forces are generally not clear, unlike the case for inertia and stiffness forces. There is advanced research results to identify a general model of damping [3] or the estimation of damping in a random vibrating system [4].

The most common approach is to use viscous damping or Rayleigh damping where it is assumed that the damping matrix is proportional to the mass *[M]* and stiffness matrices *[K],* or:

$$[C] = \alpha[M] + \beta[K]$$

For large systems, identification of valid damping coefficients α and β, for all significant modes is a very complicated task.

This paper presents the theoretical basis of event simulation together with a methodology to incorporate damping for free standing systems with a large degrees of freedom, including transmission line towers, wind mill, antenna or highmast towers.

[1] Algor Inc. – Pittsburg located, advanced Finite Element Method software developer.

1. Mechanical Event Simulation Concept.

Event simulation as an engineering methodology is vastly different from the techniques that have been taught to engineers since the onset of formal engineering training, beginning with the Greek Mathematician Archimedes, around 200 BC. Event simulation is the process of engineering, by simulating a physical event in a virtual laboratory. To perform an engineering analysis using event simulation, a different viewpoint from that of classical stress analysis is required.

Hooke's law which states that force is a linear function of displacement forms the basis of classical stress analysis and thus, of modern finite element stress analysis.

In finite element analysis, the matrix equation $\{F\} = [K]\{U\}$ is solved for the displacement vector, $\{U\}$, from the force vector, $\{F\}$, and the stiffness matrix, $[K]$. Subsequently, the stresses are calculated from the equation $\{\tau\}= E\{\varepsilon\}$, where $\{\varepsilon\}$ is the strain vector, which is a normalized displacement vector. E is Young's modulus that corresponds to Hooke's constant, k.

This method works well if the analyzed system is always at rest. However, in practical mechanical or structural engineering the static case would never dictate the design. The design must consider the "worst case scenario" which generally occurs when the system is in motion, when the forces and thus the stresses are greater than those under static conditions.

This is where virtual engineering enters the design process: it allows us to simulate the entire event, not simply obtain a static solution. A useful by-product of simulating the event is the forces generated by motion.

The theory behind Mechanical Event Simulation is based on the general finite element equilibrium equations clearly presented in 1982 by Bathe [5].

Later on, Weaver and Timoshenko [6], Inman [7] and Hutton [8] had major contributions in modeling, and incorporating the damping into the free vibration mathematical models.

The derivation of MES equations is in detail presented by author on: http://www.wceng-fea.com/dil.pdf and briefly presented below.

For a general three-dimensional body, discretized in m finite elements, under external surface forces f^S, body forces f^B and concentrated forces F^i,

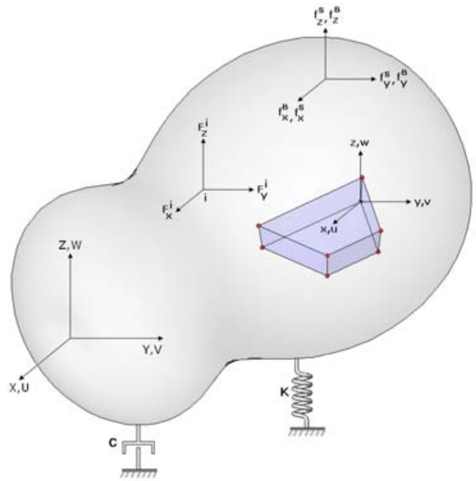

Fig. 1.1 General three-dimensional body.

the matriceal equilibrium equations of the element assemblage is:

$$M\ddot{U} + C\dot{U} + KU = R \tag{1.1}$$

Where:

- C is the damping matrix of the element assemblage,

$$C = \sum_m \int_{V^{(m)}} k^{(m)} H^{(m)^T} H^{(m)} dV^{(m)} = \sum_m C^{(m)} \tag{1.2}$$

- M is the mass matrix of the element assemblage,

$$M = \sum_m \int_{V^{(m)}} \rho^{(m)} H^{(m)^T} H^{(m)} dV^{(m)} = \sum_m M^{(m)} \tag{1.3}$$

- K is the stiffness matrix of the element assemblage,

$$K = \sum_m \int_{V^{(m)}} B^{(m)^T} C^{(m)} B^{(m)} dV^{(m)} = \sum_m K^{(m)} \tag{1.4}$$

- R is the matrix of the resultant of the applied loads on three-dimensional body, and:
    - $k^{(m)}$ is the elemental damping property;
    - $H^{(m)}$ is the elemental displacement interpolation matrix;
    - $\rho^{(m)}$ is the elemental mass density;
    - $B^{(m)}$ is the strain-displacement matrix;
    - $C^{(m)}$ is the elemental damping matrix.

Equation (1.1) is the basic equation of virtual engineering; note how it models the combination of motion, damping and mechanical deformation. If the stresses are still of interest, they can be calculated at any time during the analysis by application of the formula $\{\tau\} = E\{\varepsilon\}$, where $\{\varepsilon\}$ (the strain vector) is easily obtained from the displacement vector $\{U\}$.

2. How to incorporate damping into Mechanical Event Simulation?

In practice it is difficult if not impossible to determine for general finite element assemblages the element damping parameters, in particular because the damping properties are frequency dependent. For this reason, the matrix C is in general not assembled from element damping matrices. Instead, it is constructed using the mass matrix and stiffness matrix of the complete element assemblage together with experimental results on the amount of damping.

Equation (1.1) can be transform in terms of generalized displacements $X_{(t)}$ using the transformation:

$$U_{(t)} = PX_{(t)} \tag{2.1}$$

Where P is a square matrix and $X_{(t)}$ is a time-dependent vector of order n.

Theoretically, there can be many different transformation matrices P, which would reduce the bandwidth of the system matrices. However in practice, an effective transformation matrix is established using the displacement solutions of the free vibration equilibrium equations with damping neglected,

$$M\ddot{U} + KU = 0 \tag{2.2}$$

With solution having the form

$$U = \phi \sin \varpi (t - t_0) \tag{2.3}$$

Where ϕ is a vector of order n, t the time variable, t_0 a time constant, and ω a constant identified to represent the frequency of vibration (rad/sec) of the vector ϕ.

Substituting (2.3) into (2.2) will be obtained the generalized eigenproblem, from which ϕ and ω must be determined,

$$K\phi = \varpi^2 M\phi \tag{2.4}$$

The eigenproblem in (2.4) yields n eigensolutions (ω_1^2, ϕ_1), (ω_2^2, ϕ_2),... (ω_n^2, ϕ_n), where the eigenvectors are M-orthonormalized; i.e.,

$$\phi_i^T M \phi_j \begin{cases} = 1; i = j \\ = 0; i \neq j \end{cases} \tag{2.5}$$

and

$$0 \le \varpi_1^2 \le \varpi_2^2 \le \varpi_3^2 \ldots \le \varpi_n^2 \tag{2.6}$$

The vector ϕ_i is called the i^{th}-mode shape vector, and ω_i is the corresponding frequency of vibration (rad/sec). It should be emphasized that (2.2) is satisfied using any of the n displacement solutions $\phi_i \sin \omega_i(t-t_0)$, $i=1,2\ldots,n$.

Defining a matrix Φ whose columns are the eigenvectors ϕ_i , a diagonal matrix Ω^2 which stores the eigenvalues ω_i^2 on its diagonal and because the eigenvectors are M-orthonormal, equation (1.1) becomes:

$$\ddot{X}_{(t)} + \Phi^T C \Phi \dot{X}_{(t)} + \Omega^2 X_{(t)} = \Phi^T R_{(t)} \tag{2.7}$$

which is valid only when the damping matrix is proportional with the mass and stiffness matrix $[M]$ and $[K]$.

$$[C] = \alpha[M] + \beta[K] \tag{2.8}$$

The analytical methodology to arrive to orthogonal transformation (2.7) is in detail presented by author on: http://www.wceng-fea.com/dil.pdf.

For large systems, identification of valid damping coefficients α and β, for all significant modes is a very complicated task.

As shown by Chowdhury and Dasgupta [9], the relationship between damping ratio and natural frequency for a free standing structure looks like in Fig..2.1

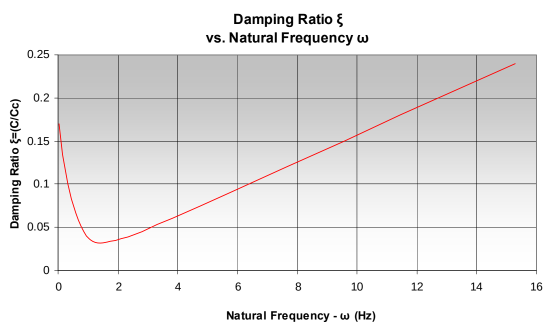

Fig.2.1. Damping Ratio Versus Natural Frequency.

Based on the fact that above frequencies close to one Hertz the relationship is practically linear one could set up a methodology [9] to estimate, the Rayleigh damping coefficients which will approximate the damping for all frequency modes in linear range.

The applicability of this methodology was investigated by author for a large array of transmission, antenna and highmast towers which cover practically all potential applications for these structures.

Was set up a methodology applicable for tubular multisided tapered free standing structures with a height less than ~50m.

The use of this methodology in conjunction with Mechanical Event Simulation is a completely new approach in Structural Dynamic Analysis giving to the design engineer more degrees of freedom in investigating the response of the critical structural connections to cyclic induced loads which are the fatigue sources.

Methodology to calculate Rayleigh Damping Coefficients α and β

- Perform a modal frequency analysis[2] to calculate the natural frequencies; determine the *m* value for which the cumulative modal mass participation is close to 95% or higher.
- Consider the *2.5m* vibration modes;
- Select ζ_1, the damping ratio for the system's first vibration mode;
- Select ζ_m, the damping ratio for the system's m^{th} vibration mode;
- For intermediate modes *i*, where $1<i<m$, obtain ζ_i from equation (2.9) based on linear interpolation.

$$\zeta_i = \frac{\zeta_m - \zeta_1}{\varpi_m - \varpi_1}\left(\varpi_i - \varpi_1\right) + \zeta_1 \qquad (2.9)$$

- For modes greater than m ($m< i \leq 2.5m$), extrapolate the values based on equation (2.10)

$$\zeta_i = \frac{\zeta_m - \zeta_1}{\varpi_m - \varpi_1}\left(\varpi_{m+i} - \varpi_m\right) + \zeta_1 \qquad (2.10)$$

- Select first set of data: ω_1, ω_m *and* ζ_1, ζ_m.
- Based on the first set of data calculate β with equation (2.11):

$$\beta = \frac{2\zeta_1\varpi_1 - 2\zeta_m\varpi_m}{\varpi_1^2 - \varpi_m^2} \qquad (2.11)$$

Back-substituting the values of β in expression (2.12):

$$2\zeta_1\varpi_1 = \alpha + \beta\varpi_1^2 \qquad (2.12)$$

Obtain α.

- Next select a second set of data consisting of: ω_1, $\omega_{2.5m}$ *and* ζ_1, $\zeta_{2.5m}$.
- Recalculate β and α based on equations (2.11) respectively (2.12).

Now one has the three sets of data – *a, b, and c,* below:

a) Based on linear interpolation;
b) Based on data set: ω_1, ω_m and ζ_1, ζ_m..
c) Based on data set: ω_1, $\omega_{2.5m}$ and ζ_1, $\zeta_{2.5m}$.
d) Obtain a fourth set of data based on the averages of *b)* and *c).*

  - Plot the four sets of data based on equation (2.13) and check which data fits best with the linear interpolation curve for the first *m* significant modes.

$$\zeta_i = \frac{\alpha_i}{2\varpi_i} + \frac{\beta\varpi_i}{2} \qquad (2.13)$$

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[2] To estimate natural frequencies and the modal participation factors can be used a general purpose FE software (Algor, Ansys, Nastran etc.).

- Select the corresponding values for α and β as the desired values which will give the incremental damping ratio based on Rayleigh damping.

3. Numerical Application – 400 kV Transmission Tower

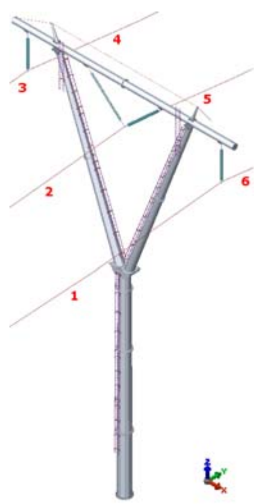

Fig. 3.1 400 kV Transmission Tower

Let's consider the transmission tower shown in Fig. 3.1.

This tower supports three 400 kV phases, has a height of 40m, 7m span between two phases, 1.2m diameter at the base and total weight of 15 tons.

The tower is anchored using 24 anchor bolts with a diameter of 38mm. To level the tower, levelling nuts are used as shown in Fig. 3.2.

Above the base plate there is a 300mm by 750mm inspection access opening with a 12.7mm thick reinforcing ring.

We will try to investigate the response of the structure considering damping, under dynamic induced forces by wind on the electrical cables and by an unexpected rupture of one of the electrical conductors.

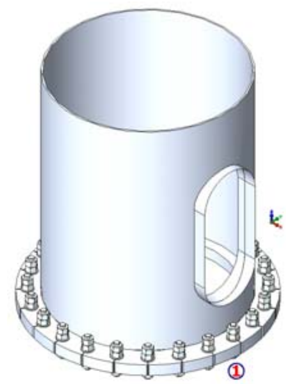

Fig. 3.2 Pole Bottom Detail

Using the methodologies presented in the design standards ([17] to [26]):

- all forces will be approximated and applied in a static fashion;
- the damping coefficients will not fit properly for all natural frequency modes;

This approach distorts the system response by eliminating the most dangerous loads, the cyclic ones, which potentially generate fatigue in the system's critical connections.

To avoid this inconvenience we will use a dynamic, fully nonlinear approach applying the Mechanical Event Simulation concept[3].

How the Mechanical Event Simulation approach works?

Let's consider a 60s mechanical event defined in Table 3.1 and Fig. 3.3.

In order to not generate excessive perturbation, the gravitational acceleration will be applied gradually from $0m/s^2$ to $9.81m/s^2$ on the system (during the first 10s). When the system is completely stabilized (at time 35s) wind pressure forces on the electrical conductors will gradually be applied.

[3] The methodology presented here is been used with success by author for many structures designed and built by West Coast Engineering Group Ltd.

Table 3.1

Mechanical Event Description

Time (s)	Gravitational Acceleration (m/s^2)	Wind Pressure Force on Cables 2-6 (N/m^2)	Wind Pressure Force on Cable 1 (N/m^2)
0	0	0	0
10	9.81	0	0
30	9.81	0	0
35	9.81	400	1200
35.1	9.81	408	0
40	9.81	1200	0
45	9.81	1200	0
45.1	9.81	0	0
60	9.81	0	0

Some instability in the system will be generated by applying various wind pressure forces on conductor 1 and simulating a rupture of this conductor (at time 40s).

The problem requires plotting the axial stress in bolt #1 and to checking the stress distribution around the (hand) hole reinforcing ring, and in the weld between the base plate and shaft during the mechanical event.

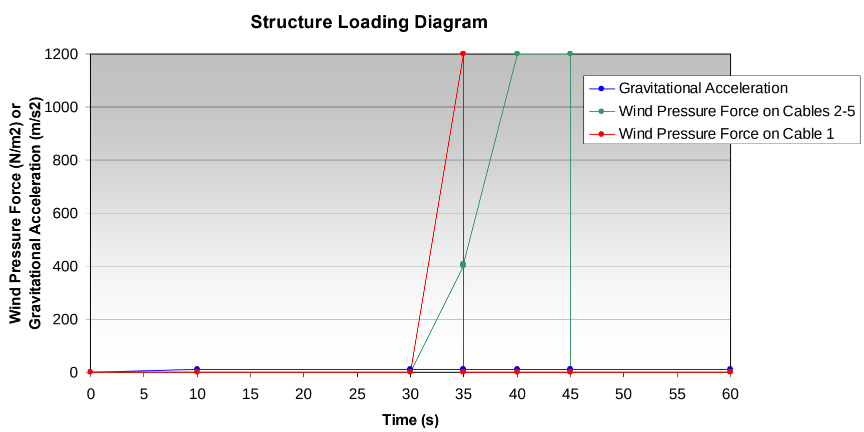

Fig. 3.3 Mechanical Event Simulation – Loading Diagram

Algor software was used to simulate this mechanical event. For these types of complicated nonlinear applications, the author proposes a procedure which has been incorporated as a standard design procedure into the West Coast Engineering Group Ltd. design process (fully detailed at this web link: http://www.wceng-fea.com/dil.pdf) briefly outlined below:

1) Develop a beam finite element model which simulates accurately the geometrical and structural details of the investigated system which will be used to determine the system's natural frequency modes.
2) Using the methodology presented in chapter 2 calculate the Rayleigh damping coefficients.
3) Using truss (or beam) finite elements simulate the electrical conductors.
4) Apply the loads (shown in Table 3.1) and boundary conditions to simulate the rupture of conductor #1.
5) Choose the start Time Step for the nonlinear solution: $\omega_l/10$.
6) Graph the results in all critical areas (above the base plate connection and all flanged connections).
In this example, focus is on the pole bottom portion so the dynamic induced loads were graphed at 2m above the base plate and are presented in Figs. 3.4 to 3.6.

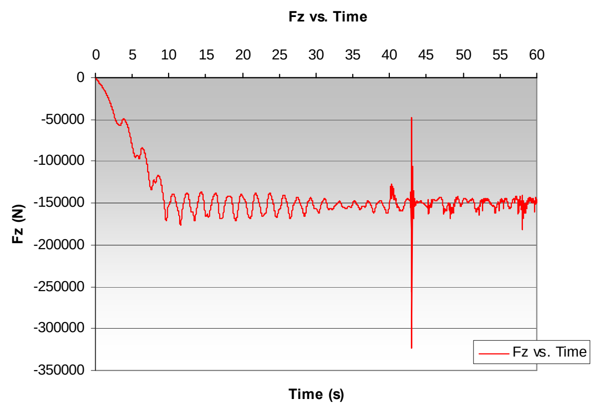

Fig. 3.4 400 kV Transmission Tower – Fz Dynamic Induced Load.

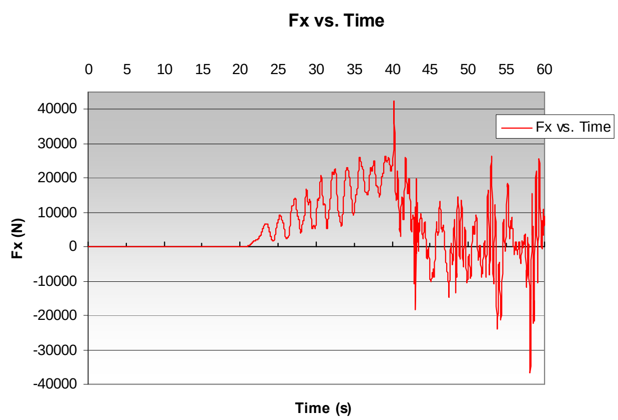

Fig. 3.5 400 kV Transmission Tower – Fx Dynamic Induced Load.

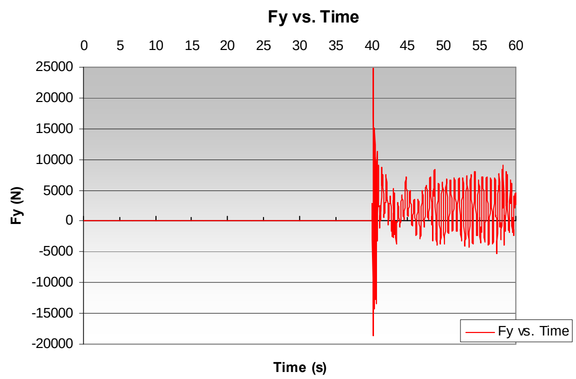

Fig. 3.6 400 kV Transmission Tower – Fy Dynamic Induced Load.

7) Develop a detailed finite element model for the area of interest (in our case the bottom of the pole as shown in Fig. 3.7) and check the stability of this model prior to applying the dynamic induced loads captured from the beam finite element model.

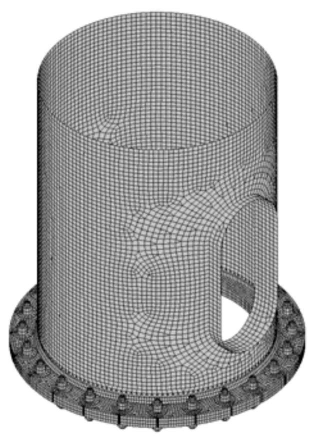

Fig. 3.7 Pole Bottom – Detailed Finite Element Model.

Correct application of the boundary conditions is critical for the model's response to the dynamic induced loads.

In our specific case we were interested in tracking the stress distribution around the hand hole reinforcing ring and in the welded connection between the base plate and the shaft.

We also want to graph the axial stress in anchor bolt #1.

The finite element model was built using plate finite elements to simulate the shaft and hand hole reinforcing ring, brick finite elements to simulate the weld between the shaft and the base plate (two layers), three layers of brick finite elements to simulate the base plate, and brick finite elements to simulate the washers and nuts.

The anchor bolts were simulated using beam finite elements.

The model also simulates pre-tensioning of the anchor bolts which will induce a high pressure at the contact between the washers and the base plate (see Fig. 3.8).

The model was checked for different mesh sizes and the results were convergent.

The model was run for the above described load case (see Fig.3.3) and the results are presented in figs. 3.8 and 3.9.

In Fig.3.8 it can be seen clearly how the areas of interest respond to the applied loads. The highest stress is at contact between the washers and the base plate, above the shaft – base plate welded connection and around the welded hand hole reinforcing ring.

It is very important to plan the work before building a finite element model!

In this case our model is built to permit even further investigation of the pole bottom, easily.

For example: using plate finite elements to simulate the hand hole reinforcing ring, it is easy to investigate the effect of thickness of the hand hole reinforcing ring on the stress distribution around this opening.

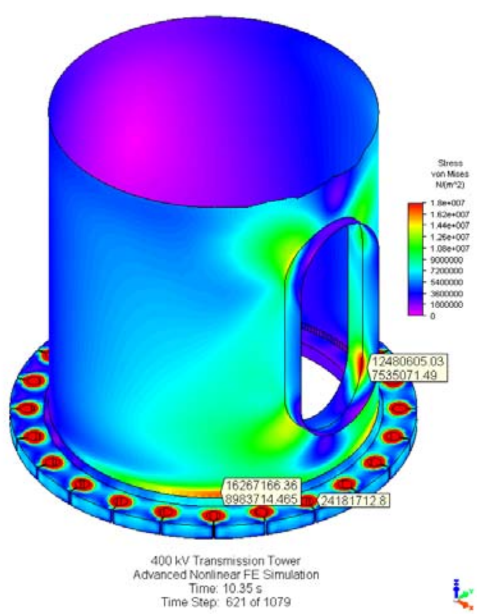

Fig. 3.8 400 kV Pole Bottom – Stress Distribution

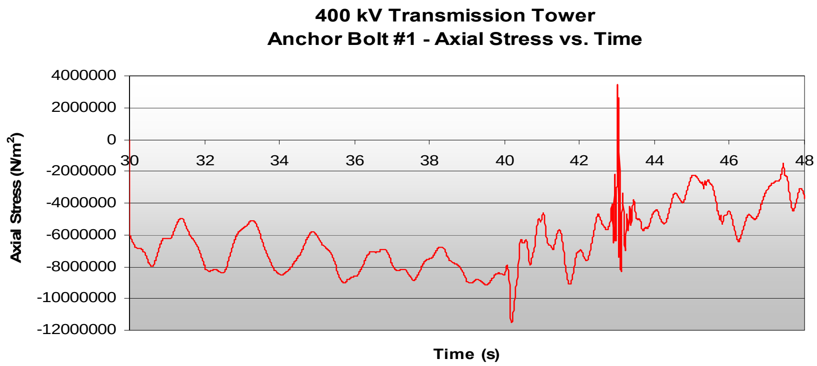

Fig. 3.9 Axial Stress Variation in Bolt #1.

In Fig.3.9 is presented the axial stress variation in bolt#1 between t=30s and t=48s during the analyzed mechanical event.

It is very important to observe that the dynamic induced loads applied to the model triggered the first two natural frequency modes (ω_1=0.407 Hz and ω_2=02.064 Hz).

The model presents behaviour of the areas of interest with a very high degree of detail.

Conclusions

This Paper presents a modern, new approach in designing free standing structures that are subject to dynamic induced loads, the sources of structural fatigue.

The procedures outlined in this paper involve the most advanced engineering simulation concept – Mechanical Event Simulation – to investigate, analyze, and optimize very complex geometries (see Fig.4.1) that are usually the most critical areas for free standing structures.

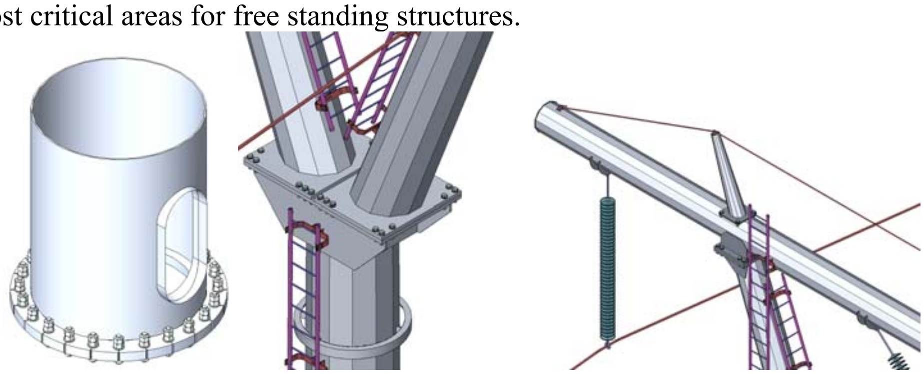

Fig.4.1 Critical Connection for a Transmission Tower

These complicated connections, can not usually be investigated using closed form solutions. The high degree of detail makes it practically impossible for even a very experienced design engineer, to predict the system's response to dynamic induced loads.

Most of the design standards ([17] to [26]) present methodologies to design the structures for fatigue, but lack in providing methods to realistically account for the fatigue sources – being the interactions between the analyzed system and the (surrounding) real world elements, which in most cases are of nonlinear nature.

The new design approach proposed in this paper places the system in direct contact with the surrounding environment and calculates the loads based on this interaction.

Using this method the engineer no longer has to approximate the loads and to apply them statically. The simulated interaction will be a realistic one triggering the fatigue sources which are the cyclic loads.

When analyzing the effect of cyclic loads on systems, it is very important to account for the damping effect. Some design standards and technical literature do offer values for damping ratios determined for the system's first natural frequency mode.

As presented above, interaction between the system and its surrounding real world elements will likely trigger more than one frequency mode. Thus it is important to use Rayleigh coefficients for a good approximation of damping, at higher frequency modes as well.

A method to account for damping is also outlined in this paper and its applicability to the most common free standing structures checked.

The methodology presented in this paper was checked using Algor simulation software that incorporates the necessary provisions to implement it.

All simulation procedures were developed and tested by the author as a part of the research and development program ”Stability of Free Standing Structures Under Dynamic Induced Loads” initiated by the author, at West Coast Engineering Group Ltd.

Some results and animated files can be seen on the West Coast Engineering Group Ltd. web site: www.wceng-fea.com.

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