# OPTIMIZATION OF TEMPORARY STEEL GRANDSTANDS BASED ON STATIC AND DYNAMIC BEHAVIOR

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**Abstract**. *An inspected temporary steel grandstand presenting static and dynamic problems was taken as a case study to explore the use of optimization routines in the design. Taking into account restrictions in the values of stresses and natural frequencies of the structure, an optimum design was obtained using the computer code ANSYS.*

*The major dynamic problem was the potential resonance in the lateral direction. The bracing system is highly important in this case in order to maintain the natural frequencies of the structure out of the critical frequency range of the lower harmonics of the excitation produced by human movements.*

*Static and modal analyses were performed to identify structural elements presenting design problems and also critical modes of vibration. The structure was optimised using ANSYS algorithms, defining the stress level and fundamental frequency as state variables, the cross section dimensions of the elements as the design variables and the total mass as the objective function. The algorithm and rules for an adequate placement of the bracing elements were explored.*

*A procedure is proposed to find a better practical way to attend both static and dynamic requirements for the design of such structures by employing rules to place the bracing system and optimization of cross section dimensions.*

Keywords. *Temporary grandstands, optimization, bracing system, vibration*.

## 1. Introduction

Temporary steel grandstands are structures assembled on site and composed of bars and connectors, being conceived mainly for use in public activities. These structures are subject to static and dynamic loads, the latter due to the movement of the spectators. Historically, the construction and use of demountable grandstands goes back to century V AD, in public events in ancient Greece (Piqué, 1997).

Recent reported failures have occurred in such structures due to the absence of a clear definition of the procedures for the design, assembling and inspection. These failures include the total collapse, like the one occurred in May 1992 in Corsica, in which there were seventeen casualties and more than 2500 people were injured. Another case occurred in 1994 in London, where 40 people were severely injured (Ji & Ellis, 1999). There have also been case reports of accidents with temporary grandstands in Brazil, like the one that occurred in Grajaú (SP) in 1995, in which 50 people were injured, or recently in a rodeo in São Paulo (2002), where 80 people were injured after the partial collapse of a grandstand.

Site inspections carried out in prototype grandstands and initial analyses of these structures have shown an apparent uncertainty in the static design and also a dynamic design being disregarded (Marinho, 2000). The inspections also showed that the geometry of such structures vary among them and there is no procedure to place the bracing system. The main dynamic problem of these structures is the potential resonance in the lateral direction due to synchronized lateral movements of the spectators (Littler, 1996). It was suggested that the bracing bars should be placed in such a way that the natural frequencies of the structure remained out of the frequency range of the lower harmonics of the excitation (Ji & Ellis, 1997).

In this work, a case study of a temporary inspected steel grandstand is presented in which the static and dynamic design were examined. The use of optimization routines was explored, taking into account restrictions in the value of the fundamental frequency of the structure in order to avoid resonance problems. Considering costs and safety, the aim is to reach an optimum design, by changing the cross sectional dimensions of structural components to minimize the total mass of the structure.

The structure was initially modelled using the finite element (FE) computer code ANSYS (2001). A static analysis was conducted to help in identifying structural elements incorretly designed. A modal analysis was subsequently carried out to identify critical vibration mode shapes, according to the restrictions imposed to the natural frequencies of the structure. In sequence, the structure was optimized employing routines presented in the computer code ANSYS (2001), defining the fundamental frequency and the stress levels as state variables, cross section dimensions of the elements as design variables and the total mass of the structure as the objective function. In parallel, rules for an adequate placement of the bracing bars were discussed and their effect in helping to reach an optimum design analysed.

## 2. Analysis of the existing structure

The technical specifications of the prototype, the finite element modeling, static and modal analyses, determination of the stress levels, natural frequencies and mode shapes of the inspected structure, identified here as grandstand AR1, are discussed.

### 2.1. Technical specifications of the structure and modeling

The main material properties and geometric dimensions of the structural components are listed below in Tab. 1 and were based on information provided by the owner of the structure and the manufacturers of the structural components. The following list of symbols apply:

-$D_i$ = external diameter of bar i;
-$e_i$ = thickness of bar i;
-$e_b$ = thickness of the seats;
-$f_y$ = yielding limit;
-E = modulus of elasticity;
-ν = Poisson's ratio;
-$m_{esp}$ = specific mass;

Table 1. General characteristics of the geometry and materials

| Grandstand AR1 | | |
|---|---|---|
| Characteristics | Steel | Wood |
| $D_1$ (mm) | 50,80 | - |
| $e_1$ (mm) | 3 | - |
| $D_2$ (mm) | 38,10 | - |
| $e_2$ (mm) | 3 | - |
| $D_3$ (mm) | 31,75 | - |
| $e_3$ (mm) | 3 | - |
| $D_4$ (mm) | 12,70 | - |
| $e_4$ (mm) | 1,5 | - |
| $e_b$ (mm) | - | 20 |
| $f_y$ (MPa) | 250 | 82,90 |
| E (GPa) | 210 | 22,74 |
| ν | 0,3 | 0,2 |
| $m_{esp}$ (kg/m³) | 7850 | 1143 |

The steel structure is composed by hollow circular bars in a 3-D arrangement, with standard cross section dimensions and length. The module of the grandstand is 2,30 m large and is made by an arrangement of bars of varied length and by wood seats. The module have 12 stairs and each stair is 40 cm high. The structure is simply supported on the ground (Fig. 1) and the FE model developed is presented in Fig. (2), being composed of four modules.

Figure 1. Grandstand AR1

Two types of finite elements were adopted in the modeling. For the steel hollow bars, the ANSYS element identified as PIPE16 was employed, being a uniaxial element with tension, compression, torsion and flexural capabilities (ANSYS, 2001). The element has six degrees of freedom in each of the two nodes: linear translations in the x, y and z directions and rotations around these axes. As for the seats, the shell element identified as SHELL63 was selected. This element also presents the same six degrees of freedom in each of its four nodes. The entire FE model had 950 elements and 530 nodes.

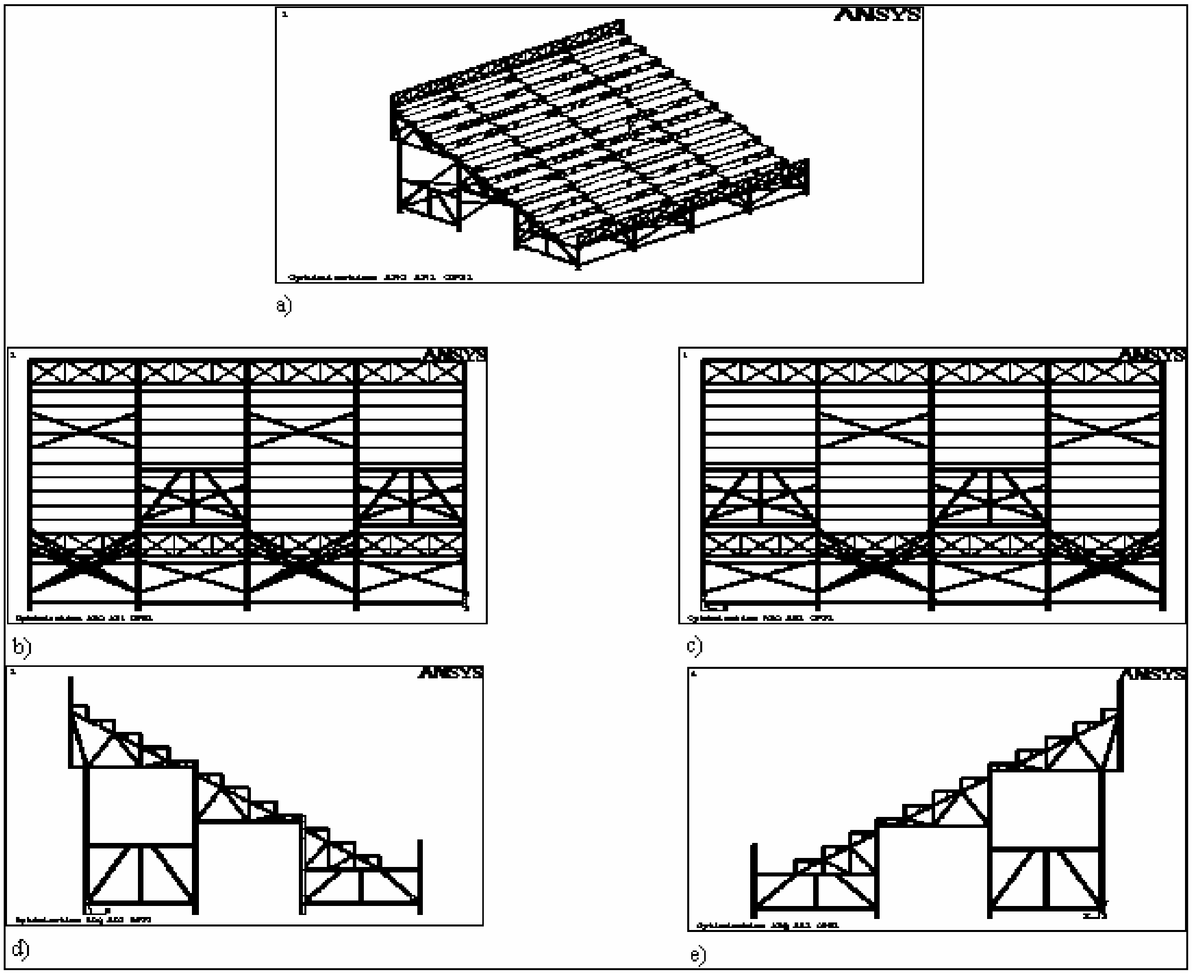


Figure 2. Model of the structure: a) perspective, b) frontal view, c) back, d) left side and e) right side

### 2.2. Design features

*Static Analysis*: Design checks were carried out by applying the guidelines of the brazilian code NBR 6120/80(1980), which defines a static load of 4 kN/m² for this type of structure, and the codes NBR 8800/86 (1986) and NBR 7190/96 (1996).

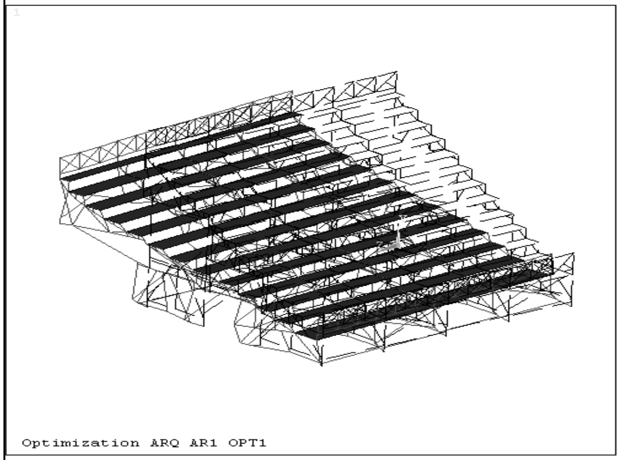
The following ultimate states were considered: elastic buckling, plastic buckling, local buckling and crushing with yielding of the whole cross section. This resulted in an ultimate stress of 94,9 MPa. It was noted that the internal forces in several bars were beyond their ultimate capacity, reaching in some cases stress values up to 163 MPa.

*Modal Analysis*: The first five natural frequencies of the structure together with a plot of the mode shape of interest can be seen in Fig. (3).

The fundamental frequency had a value of 2,36 Hz and is related to a lateral mode shape. Several references can be found in the literature regarding vibration problems in these structures and are summarized elsewhere (Marinho, 2002). Littler (1996) reported tests in forty demountable steel grandstands, finding natural frequencies in the lateral direction in the range from 1,8 to 6,0 Hz for empty structures. He also reported that 40% of the grandstands investigated presented fundamental frequencies in the lateral direction having values below 4 Hz.

It is suggested (Littler, 1996) that in the design of demountable steel grandstands, a natural frequency above 4 Hz in the lateral direction should be pursued for the empty grandstands. According to Littler (1999), this limit would set the structure free of the effect of synchronized movements of individuals, which are in the range from 1,5 to 3,5 Hz. On the other hand, the consideration of the empty structure is related to the fact that the presence of individuals, particularly in a situation of full occupancy, induces changes on the natural frequencies which are not easily quantified (Littler, 1996).

The lower limit of 4 Hz would also avoid the effect of the activity of jumping and clapping hands, reported to produce excitation in the lateral direction in the range from 1,8 to 3,4 Hz (Bachmann and Ammann, 1987).



| Modes Shapes | Frequency (Hz) |
|---|---|
| 1st(lateral) | 2,36 |
| 2nd(lateral-shear mode) | 4,43 |
| 3rd(front-to-back) | 4,44 |
| 4th(lateral-shear mode) | 5,97 |
| 5th(vertical) | 6,70 |

Figure 3. Natural frequencies and first mode shape in the lateral direction

In this way, the fundamental frequency of the case study was 2,36 Hz, which is below 4 Hz, and this suggests potential problems with the dynamic behavior of the structure.

## 3. The method of optimization

The built-in First Order Method in the computer code ANSYS (2001) was employed in the optimization procedure. This method uses information from the derivate, that is, gradients of the dependent variables with respect to the design variables. It is highly accurate and produces good results for problems in which the dependent variables vary widely over a large range of the design space. Three types of parameters characterize the optimization process: Design Variables, State Variables, and the Objective Function.

### 3.1. Definition of the optimization parameters

The following parameters were defined: 1. Design Variables (DV's), chosen as the diameter and the thickness of the metallic tubes and the thickness of the seats. They are independent quantities that are varied in order to achieve the optimum design. Upper and lower limits are specified to serve as constraints to the design variables; 2. State Variables (SV's), which are quantities that constrain the design. They are also known as dependent variables, and are typically response quantities that are functions of the design variables. A state variable may have a maximum and minimum limit and, in this case, these variables were chosen as stress values and fundamental frequency; 3. Objective Function (OF) which is the function that one wants to optimize, in this case the total mass of the structure.

The problem is represented mathematically by:

$$x = [\, x_1, x_2, x_3 .... x_n \,] \qquad (1)$$

where x are the design variables. These variables are subject to *n* constraints with upper and lower limits, that is,

$$\underline{x}_i \le x_i \le \overline{x}_i \qquad (\, i = 1, 2, 3, \ldots, n) \qquad (2)$$

where n is the number of design variables.

The constraints are often referred to as side constraints and define what is commonly called the feasible design space. Now, the problem can be formulated in terms of minimizing

$$f = f(x) \qquad (3)$$

subject to

$$g_i(x) \leq \overline{g_i} \qquad (i = 1, 2, 3, \ldots, m_1) \tag{4}$$

$$\underline{w_i} \leq w_i(x) \leq \overline{w_i} \qquad (i = 1, 2, 3, \ldots, m_2) \tag{5}$$

where f is the objective function, $g_i$ and $w_i$ are state variables, with underbars and overbars representing lower and upper bounds, respectively, and $m_1$ and $m_2$ are the number of state variable constraints with several upper and lower limit values.

The constrained problem expressed in Eqs. (1) to (5) is transformed into an unconstrained one via the use of penalty functions. Derivatives are formed for the objective function and the state variable penalty functions, leading to a search direction in the design space. Several steepest descent and conjugate direction searches are performed during each iteration until convergence is reached. Each iteration is composed of stages that include search direction and gradient computations.

## 4. Optimization of the structure

The initial thought was to reduce the mass of the structure considering that the design was overconservative to compensate absence of dynamic design and also the simplified static design. However, as it was previously discussed, the actual situation was the opposite. Furthermore, the fundamental frequency was below the recommended lower limit. Therefore, the optimization process should correct the design by increasing cross section dimensions.

### 4.1. Initial optimization

In the first attempt to optimize, convergence was achieved, resulting in a design in accordance to the restrictions in stress, although it was not possible to obtain fundamental frequencies above 4 Hz. This suggested that the initial design of the structure would not result optimized for the imposed restrictions and design variables that were chosen.

Analyses carried out showed the the bracing system would be the key system to find a solution for the problem. It was therefore necessary to investigate in detail such a system to find how the bracing bars should be ideally disposed.

Ji & Ellis (1997) discussed the role of the bracing system for temporary grandstands. Based on studies in plane frames, they proposed five criteria to place, include and/or rearrange the members of the bracing system, seeking an increase in the lateral stiffness and therefore in the fundamental frequency in this direction. The five criteria proposed by them were:

1. Bracing members in different storeys should be placed from the top to the base of the structure;
2. Bracing members in different storeys should be directly linked where possible;
3. Bracing members should be linked in a straight line where possible;
4. Bracing members at the top of adjacent bays should be directly linked where possible;
5. If extra bracing members are required, they should be placed following the above four criteria.

As stated by Ji & Ellis (1997), two concepts were employed to derive the aforementioned criteria and produce a stiffer pinned structure: the direct force path and a uniform force distribution. They provided details and application of these concepts in their paper. Marinho (2000) investigated the application of these five criteria in three-dimensional simple frames and found out that they were also effective in increasing the stiffness.

### 4.2. Proposed changes in the structure

An initial optimization of the placement and arrangement of the bracing members was therefore carried out in the prototype grandstand, following the aforementioned five criteria. The optimized bracing system can be seen in Fig. (4). After the changes made in the bracing system, the fundamental frequency of the structure was increased from 2,36 Hz to approximately 3,5 Hz.

### 4.3. Final optimization

Although the increase in fundamental frequency was significant, it was still below the lower recommended limit of 4 Hz. However, departing now from the structure having the new bracing system, the ANSYS optimization routine was again applied.

Initial modeling**:**
-initial diameter and thickness of the tubes and seat:
$D_1$ = 58,80 mm and $e_1$ = 3 mm;
$D_2$ = 38,10 mm and $e_2$ = 3 mm;
$D_3$ = 31,75 mm and $e_3$ = 3 mm;
$D_4$ = 12,70 mm and $e_4$ = 1,5 mm; and

thickness of the wood seats $e_b$= 20 mm.
- Initial fundamental frequency: 3,5 Hz;
- Support conditions: simply supported;
- Initial mass: wood elements = 1566,8 kg; metallic structure = 1326,3 kg; total = 2893,1 kg.

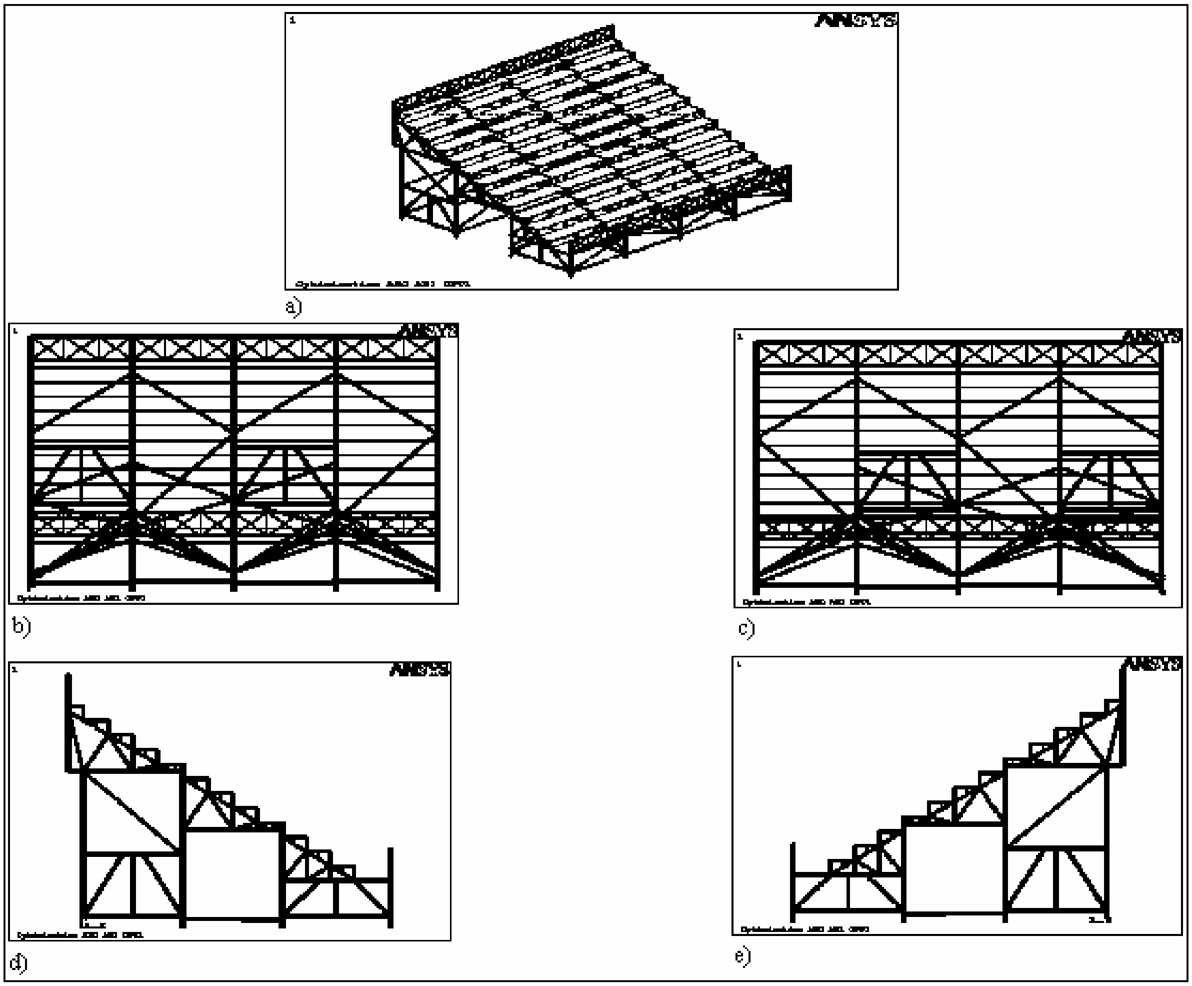


Figure 4. Structure having the bracing system optimized: a) perspective, b) front view, c) back, d) left side and e) right side

Optimization Module: Design limits - Table (2) presents limit values for the design variables. The limits define the range of diameters and thicknesses which are commercially available.

Table 2. Commercially available limits for the design variables

| Design Variable (DV'S) | Limits | |
|---|---|---|
| | Minimum value (mm) | Maximum value (mm) |
| $D_1$ | 38,10 | 63,50 |
| $e_1$ | 2,0 | 4,25 |
| $D_2$ | 33,50 | 50,80 |
| $e_2$ | 2,0 | 3,75 |
| $D_3$ | 25,40 | 50,80 |
| $e_3$ | 2,0 | 3,75 |
| $D_4$ | 12,70 | 31,75 |
| $E_4$ | 2,0 | 3,0 |
| $e_b$ | 12 | 25 |

State Variables (SV's): SMAXI, SMAXJ (limiting stress values at the endings of the bar (at nodes i and j)) and FREQ (fundamental frequency of the structure). These are the restrictions related to Eqs. (4) e (5).

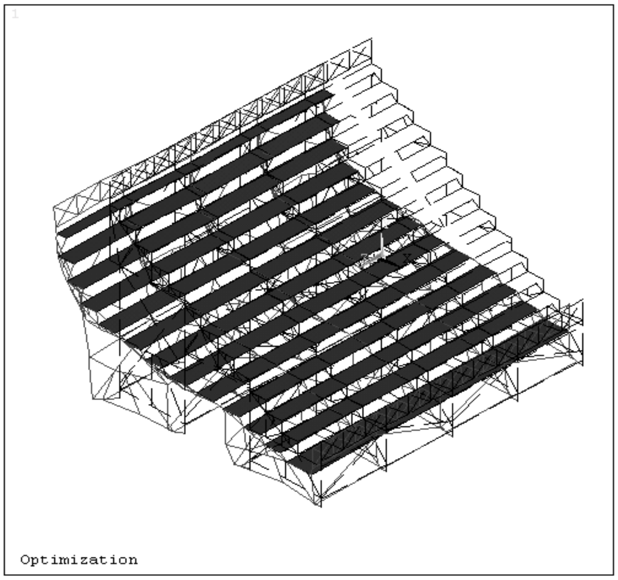
Design Limits:

stress : 94,9 MPa;

frequency: Minimum value = 4 Hz; Maximum value = 7 Hz (the upper limit of 7 Hz was defined only to attend a demand of the optimization algorithm).

Objective function: total mass of the structure, a tolerance of 1 kg and a maximum number of iterations set to 25.

The optimum fundamental frequency and associated mode shape and the other first four natural frequencies of the structure are presented in Fig. (5).



| Mode Shape | Frequency (Hz) |
|---|---|
| 1st (lateral) | 4,85 |
| 2nd (front-to-back) | 7,21 |
| 3rd (lateral) | 7,59 |
| 4th (front-to-back) | 9,22 |
| 5th (vertical) | 10,54 |

Figure 5. First mode shape and natural frequencies of the structure after optimization

The result of the optimization is presented in Tab. (3), calling attention to the fact that the diameters and thicknesses presented are commercial values.

Table 3. Optimized values of the design variables and other parameters

| Design variables/Parameter | Optimum values |
|---|---|
| $D_1$ (mm) | 63,50 |
| $e_1$ (mm) | 3,0 |
| $D_2$ (mm) | 50,80 |
| $e_2$ (mm) | 3,75 |
| $D_3$ (mm) | 50,80 |
| $e_3$ (mm) | 2,0 |
| $D_4$ (mm) | 12,70 |
| $e_4$ (mm) | 3,0 |
| $e_b$ (mm) | 20 |
| SMAX (MPa) | 94,1 MPa |
| FREQ (Hz) | 4,85 |
| TOTAL MASS (kg) | 3599,82 |

## 5. Analysis and discussion

The optimized model had 972 elements and 530 nodes. The optimization of the bracing system caused an increase of 12 bars in comparison to the original grandstand. It should be noted that this was necessary to have as the starting point an structure that could be optimized, keeping the stress values below the limit and the fundamental frequency above 4 Hz.

The five criteria proposed by Ji and Ellis (1997) to optimize the bracing system are simple and easy to be applied while assembling the structure. From a dynamic point of view, the application of these criteria resulted in a structure that could be optimized, presenting the fundamental frequency above the defined limit.

It should be noted that the total mass of the structure increased to satisfy the restrictions in terms of stress levels since the original estructure was under risk of collapse. However, the final dimensions obtained for the bars were related to a condition of minimum mass for the structure to satisfy the design criteria. The cross sectional areas of the bar elements changed from the original values of 4,5 cm², 3,4 cm², 2,7 cm² e 0,5 cm² to the values of 5,9 cm², 5,5 cm², 5,9 cm², e 0,9 cm², respectively. The first group of values resulted in a structure insufficient to resist the static loads.

However, it was possible to apply the optimization only after making adequate changes in the bracing system, through the application of the discussed criteria.

## 6. Conclusions

The optimization module of the software ANSYS (2001) was successfully applied to the design of demountable grandstands. One such structure was inspected and taken as a case study in this investigation.

While applying the optimization module, it was noted that the original geometry of the grandstand would not enable the grandstand to be optimized. Only after improvements made in the original design was it possible to increase the fundamental frequency of the structure to a value above the specified lower limit. The changes were focused on the bracing system and five criteria proposed in the literature to be applied to plane frames were successfully employed in the three-dimensional grandstand. This emphasizes the idea that optimization is a powerful resource to be used in design. Nevertheless, it requires a previous analysis of the conceptual design of the structure to properly work . It was shown that the bracing system is the target system to be initially improved and this system was optimized by the application of the five criteria discussed. Therefore new bars were introduced in the bracing system so as to increase the fundamental frequency of the structure.

Since the ANSYS optimization module is a tool of non-trivial use present in the software, the study presented here showed that the application of this module to frame structures is feasible. The procedure employed here of first analysing and changing the bracing system following predefined rules, and after optimizing the dimensions of the structural elements was successful in improving the design to attend both static and dynamic requirements.

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## 8. References

Allen, D. E., Rainer, J. H. and Pernica, G., 1985, “Vibration Criteria for Assembly Occupancies”. Canadian Journal of Civil Engineering. Vol 12, No 3 pp 617-623.

ANSYS, 2001, “User’s Manual. Revision 6.0”.

Bachmann, H & Ammann, W., 1987, “Vibrations in Structures Induced by Man and Machines”. IABSE Structural Engineering Documents 3e.

Ellis, B. R., Ji, T. and Littler, J. D., 1994, “The response of grandstands to dynamic loads induced by crowds”. Proceedings of 1994 Australian Structural Engineering Conference. Sydney.

Ji T. & Ellis, B. R., 1994. “Floor Vibration Induced by Dance-Type Loads: Theory”, The Structural Engineer, 72(3),pp 37-44.

Ji, T. And Ellis, B. R., 1997, “Effective Bracing Systems for Temporary Grandstands”, Structural Engineer, Vol. 75, No. 6, pp 95-100.

Ji, T. And Ellis, B. R., 1999, “The Evaluation of Sports Stadia Grandstands for Dynamic Crowd Loads at Pop Concerts in the Unit Kingdom”, Structural Dynamics – EURODYN’ 99, Balkeman, Rotterdam, pp. p37-942.

Littler, J. D., 1996, “Measuring the dynamic response of temporary grandstands”, Structural Dynamics – EURODYN’96, Balkeman, Rotterdam, pp. 907-913.

Littler, J. D., 1999, “The Dynamic Response of Three Tier Cantilever Grandstands”, Structural Dynamics – EURODYN’99, Balkeman, Rotterdam, pp. 623-628. ISBN-90-5809-056-6.

Marinho, I. J. P., 2000, ”Estudo dos efeitos de vibração em estruturas de arquibancadas temporárias”. UFPB.PIBIC;

Marinho, I. J. P., 2002, “Projeto ótimo de estruturas metálicas de arquibancadas reutilizáveis via ANSYS”. Dissertação de Mestrado, Pontifícia Universidade Católica do Rio de Janeiro_PUC-Rio, Departamento de Engenharia Civil.

NBR 6120/1980, 1980, “Cargas para Cálculo de Estruturas de Edificações”, ABNT – Associação Brasileira de Normas Técnicas.

NBR 7190/1996, 1996, “Projeto de Estruturas de Madeira”, ABNT – Associação Brasileira de Normas Técnicas;

NBR 8800/86, 1986, “Projeto e Execução de Estruturas de Aço para Edifícios”, ABNT – Associação Brasileira de Normas Técnicas.

Piqué, J. F., 1997, “A tragédia grega: ambiente e formas”. Presentation. Universidade Federal do Paraná.