Elastically connected and offset members at Seville April Fair gateways

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Abstract

On the occasion of the celebration of the April Fair, Seville's city council orders a gateway to the fairground to be built every year. These large structures, 50 meters long, 40 meters high and a variable depth of around 4 to 5 meters, are space structures composed of tubular metal elements connected by clamps, and covered by ornamental wood boards. The design of the referred spatial structure is presented as modular, able to distribute efforts in an isotropic network, so that efforts are transmitted in a uniform way. This paper investigates the problems involved in the analysis of this three dimensional structure having offset members. It intends to see if there are major differences between considering or not the modelling of the eccentricities, as well as further testing the influence of the consideration of the rigidity of the clamp, modelling it as rigid, articulated or elastic. The extent to which the modification influences the position of the eccentricities is also discussed, as this aspect is difficult to control on site.
Keywords: Seville April Fair gateways, spatial framework, tube, clamp, offset, eccentricity, rigidity.

1 Introduction

Seville April Fair gateways are constituted as large space structures composed of tubular metal elements connected together by clamps. The organization of this spatial structure is that of an orthogonal grid formed by prismatic modules diagonalized in each and every one of their faces, whose dimensions are 1'00 m in the OX direction – front elevation – variable dimension in the OY direction – transverse elevation – and 1'70 m in the OZ direction (Figure 1).

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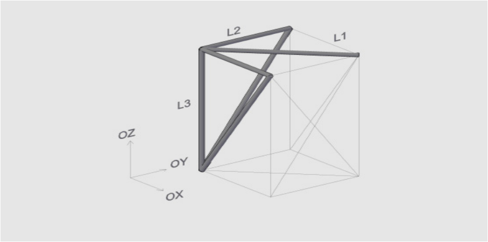

Figure 1: Prismatic module, L1 = 1’00 m, L2 = variable, L3 = 1’70 m.

Thus, it is established a variable number of vertical planes hatched with horizontal and transverse planes. The following images show the construction of the Seville April Fair gateways corresponding to different years, through repetition in the front elevation of the prismatic modules that fit the contour defined by the given shape, and depth to achieve the desired thickness.

The prismatic module is composed of A42b steel tubes, according to the former nomenclature for steel taking into account that these tubes are reused every year, now equivalent to S235 JR. The main characteristics of A42b steel are: ρ = 78’50 KN/m^3, E = $2’1\cdot10^8$ KN/m^2, fy = 260.000 KN/m^2 and fu = 420.000 KN/m^2. The tube section is constant throughout the model with an outer diameter of 48 mm. and an inner diameter of 42 mm.

The premises adopted for the configuration of this spatial structure provide a simple, cheap and fast answer for its construction every year (Figures 2–3).

Figure 2: Spatial structure during the building process.

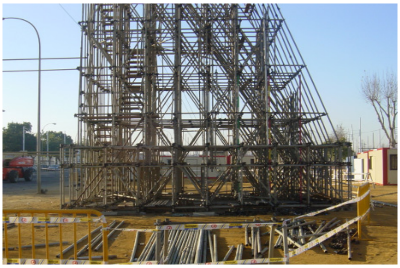

Figure 3: Spatial structure during the building process.

1.1 Tube-clamp connection system

The connection of any tube to each other is performed either by coupling clamps in the case of orthogonal planes, whose unit weight is 19 N, or by screwed inner sleeves – extension joints – whose unit weight is 16 N, when it comes to giving continuity thereto. With couplers it is ensured an effort transmission of 20 KN both in tension and compression, whereas extension joints are dimensioned to withstand the total resistant capacity of the tubes.

In the case of the couplers, the torque applied to the screw closure of the two half-rings of the coupler generates the force opposed to sliding. With this orthogonal coupler it is always possible to solve any union between two tubes without having to resort to swivel couplers, since it is always possible in our structural configuration to seek for orthogonal unions (Figures 4–5): horizontal on vertical tubes, transverse on vertical tubes, front diagonal on transverse tubes, transverse diagonal on horizontal tubes, horizontal diagonal on vertical tubes.

Figure 4: Spatial union in orthogonal planes.

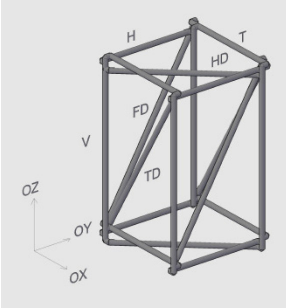

Figure 5: Spatial union in orthogonal planes.

This paper will only analyze the first type of union, which corresponds to the union in orthogonal planes. The goal is to choose the right elements for the representation of these union elements, since any deviation in the geometry or

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the mechanical properties of these lead to erroneous results. In this sense, there are two important aspects:

Firstly, it is observed that the solution used for the union in orthogonal planes produces eccentricities in the transmission of forces. Clearly, the modeling of such eccentricities complicates the formation of the global model, since it is necessary to take into account that the joint can reach up to a maximum of six directions, which corresponds to a total of twelve tubes, one in each sense for each direction, but this is further complicated when multiple tubes are arranged in parallel to achieve the necessary strength. Therefore, it is necessary to assess the influence of the consideration of these eccentricities on the final results.

Moreover, it is necessary to assess to what extent the flexibility of connections affects the behavior of the matrix structure, in addition to investigate the manner in which the mechanical properties can be determined.

2 Determination of stiffness values for orthogonal couplers

The determination of stiffness values for orthogonal couplers could not be done by experimental tests by not having the means to do so. Therefore, it was chosen to extrapolate these values from the results of a similar experimental test [1]. The test performed consisted of a short vertical tube with its ends clamped and a horizontal tube connected to it by means of an orthogonal coupler (Figure 6). The coupler's elastic characteristics were determined by performing different tests, with different load conditions, on these two connected tubes, obtaining the following values (Table 1):

Table 1: Model coupler stiffness characteristics for the referenced test.

k1 = k3 (KN/m)	k5 (KN·m)	k7 = k11 (KN·m)	k9 (KN/m)
10^9	$15'80 \cdot 10^{-3}$	$16'80 \cdot 10^{-3}$	10^9

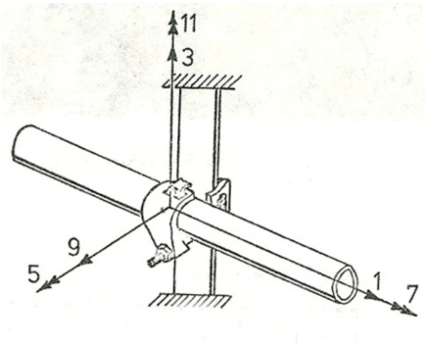

Figure 6: Numbered directions on coupler's stiffness characteristics test.

Table 2 shows the geometrical and mechanical properties corresponding to the tubular elements which concern this paper and to those used in the referenced test, in order to extrapolate the coupler's stiffness characteristics obtained above to the corresponding case of study (Table 3), taking into account the values of moment of inertia and modulus of elasticity of the tubular member.

Table 2: Geometrical and mechanical properties for tubular elements.

	Φ (m)	A (m^2)	I (m^4)	E (KN/m^2)	G (KN/m^2)
Fair gateways	$48'00 \cdot 10^{-3}$	$424'00 \cdot 10^{-6}$	$107.800'00 \cdot 10^{-12}$	$210'00 \cdot 10^{6}$	$80'77 \cdot 10^{6}$
Referenced test	$6'35 \cdot 10^{-3}$	$31'50 \cdot 10^{-6}$	$79'30 \cdot 10^{-12}$	$30'00 \cdot 10^{6}$	$4'30 \cdot 10^{6}$

Table 3: Model coupler stiffness characteristics for fair gateways.

k1 = k3 (KN/m)	k5 (KN·m)	k7 = k11 (KN·m)	k9 (KN/m)
$9'52 \cdot 10^{13}$	1503'49	1598'65	$9'52 \cdot 10^{13}$

3 Elastic and eccentric connections in spatial models corresponding to Seville fair gateways

The analysis model that will be used in this first approach will consist of the prismatic module with known dimensions (OX = 1'00 m, OY = 1'00 m, OZ = 1'70 m) repeated three times in the direction OX, twice in the direction OY and four times in the direction OZ, and it submits symmetric diagonalization to the plane OXZ (Figure 7). This model will have pinned joints at its base, and the necessary links for the provision of the symmetrical plane corresponding to OYZ will be provided. Moreover, the actions considered will be: Dead (Ornamental wood panels) = 0'20 KN/m^2, Wind = 0'84 KN/m^2, both them applied to the ends of the vertical tubes, where the ornamental wood panels that cover this structure are connected to.

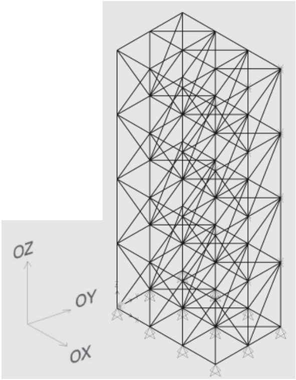

Figure 7: Analysis model considered for the study.

On the model thus generated the following analyzes were performed for further comparison, using the software SAP2000 v.11.

- No offset + Rigid joints (a).
- No offset + Released joints (b).
- No offset + Elastic joints (no extrapolated values) (c).
- No offset + Elastic joints (extrapolated values) (d).
- Offset + Rigid joints (e).
- Offset + Released joints (f).
- Offset + Elastic joints (no extrapolated values) (g).
- Offset + Elastic joints (extrapolated values) (h).

Before comparing the different analyzes, it will be detailed the way in which the different considered characteristics were assigned to the analytical models developed in SAP2000.

First, note that for modeling eccentricities of a particular spatial element it is necessary to consider a point of reference against which to set the position of the ends of that spatial element. For convenience, it will be taken as reference points the ends of elements defined as vertical tubes, so that these will be the sole spatial components whose ends will not have an eccentric position. That is why in the case of released joint as in the case of elastic joint, vertical tubes are always considered rigid at its ends [2].

Secondly, the eccentricities introduced by SAP2000 are eccentricities for calculation, not geometric. In fact, by consulting the coordinates on the ends of an element, it can be checked that they are not displaced. That is why this option does not allow generating curved geometries, and it is only valid for orthogonal geometries.

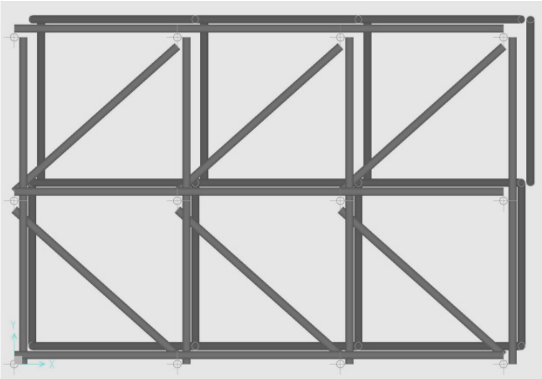

Figure 8: Analysis model with representation of eccentricities. Top view (OXY).

For the modeling of the eccentricities, the only known information is that the actual distance measured between the axes of the tubular elements to be joined, considering the presence of the coupler element itself, is of 5’50 cm. It will be necessary to assess the distance from the end of each element to the reference point considered, taking into account that it is not possible to overlap the tubes, so that this distance is always 5'50 cm. or multiple of this value. Note that the final model is symmetrical geometry, but it is not possible to make it symmetrical in eccentricities (Figure 8).

Finally, the loads must be applied to the ends of tubular elements and never in joints, since the eccentricity is assigned to the end of the bar element. If the load is applied to the joints, eccentricities would not be considered.

Once the analysis model is correctly designed, the results obtained from the different analyzes are summarized (Tables 4–5):

Table 4: Comparison between different analysis cases (a), (b), (c), (d).

STATIC LINEAR ANALYSIS (D*1'35 + W*1'5)		
	Displacement OY (Joint 85) (m)	Axial Force (Frame 1) (KN)
No offset + Rigid joints (a)	0'00370	15'44400
No offset + Released joints (b)	0'00370	15'46700
No offset + Elastic joints (no extrapolated values) (c)	0'00371	15'50000
No offset + Elastic joints (extrapolated values) (d)	0'00370	15'43800

Table 5: Comparison between different analysis cases (e), (f), (g), (h).

STATIC LINEAR ANALYSIS (D*1'35 + W*1'5)		
	Displacement OY (Joint 85) (m)	Axial Force (Frame 1) (KN)
Offset + Rigid joints (e)	0'00541	12'95500
Offset + Released joints (f)	0'00980	7'61700
Offset + Elastic joints (no extrapolated values) (g)	0'00978	7'66000
Offset + Elastic joints (extrapolated values) (h)	0'00547	12'93600

For analysis cases (e), (f), (g), (h), which represent models that consider eccentricities, it is shown that for analysis case (e) and for analysis case (h) the axial stress distribution at vertical tubes is homogeneous, but when it comes to analysis case (f) or analysis case (g) joints are no longer elastic and they become plastic (Figures 9–10) [3, 4].

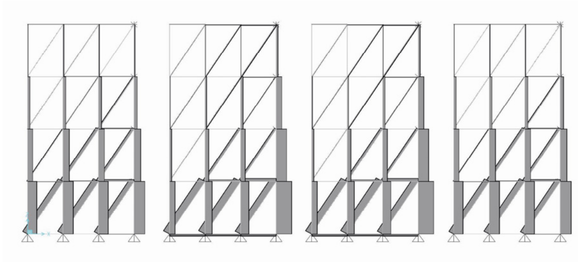

Figure 9: Axial force diagram for analysis cases (e), (f), (g), (h). Front view (OXZ).

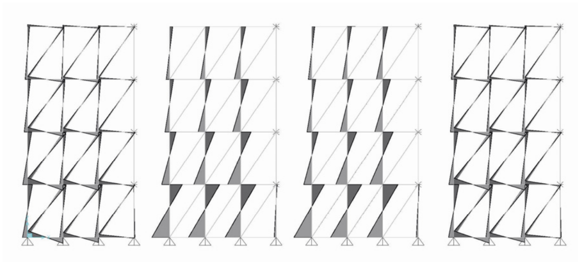

Figure 10: Moment 3-3 diagram for analysis cases (e), (f), (g), (h). Front view (OXZ).

Table 6: Analysis cases with eccentricities considering different stiffness values.

STATIC LINEAR ANALYSIS (D*1’35 + W*1’5) Offset + Elastic joints				
K (KN·m)	Displacement OY (Joint 85) (m)	Difference with rigid joints (%)	Axial Force (Frame 1) (KN)	Difference with rigid joints (%)
k7=k11 = 0’1176 k5 = 0’1106	0’00969	79’11 %	7’900	63’98%
k7=k11 = 1’176 k5 = 1’106	0’00911	68’39%	9’414	37’61%
k7=k11 = 11’76 k5 = 11’06	0’00768	41’96%	11’851	9’31%
k7=k11 = 117’60 k5 = 110’60	0’00605	11’82%	12’746	1’64%
k7=k11 = 1176’0 k5 = 1106’0	0’00550	1’66%	12’929	0’20%
k7=k11 = 11760 k5 = 11060	0’00542	0’18%	12’953	0’01%
k7=k11 = 117600 k5 = 110600	0’00541	0%	12’955	0%

3.1 Comparison of different stiffness values

The analysis performed so far shows that stiffness values are not influential if eccentricities are not considered, but they become quite important when these eccentricities are modeled [5]. The next question is to assess the importance of the stiffness values adopted, taking into account that so far only two different values have been adopted: those obtained from the experimental referenced test, and those obtained from extrapolation of the previous ones. After this assessment, it is noted that in case of elastic joints with stiffness of order 10^3 KN·m the results obtained are very similar to those obtained for rigid joints, and over the order 10^5 they are identical (Table 6 – Figure 11) [6].

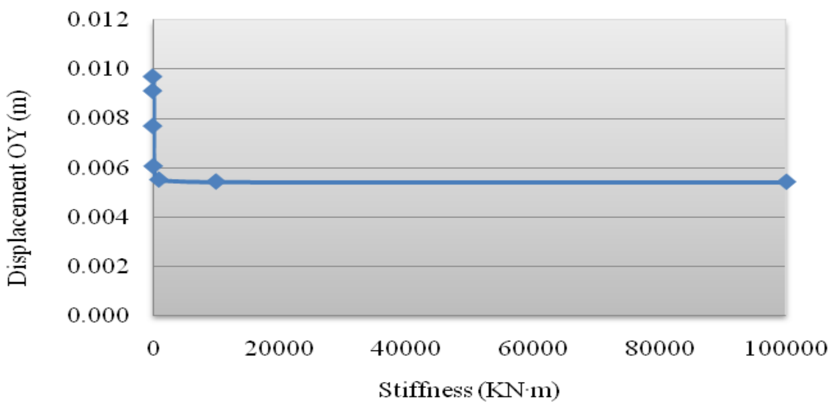

Figure 11: Stiffness value influence on horizontal displacement (OY).

3.2 Randomness in the position of eccentricities

So far it has been supposed that the position of eccentricities that has been considered is held constant during the overall construction of the structure. For example, it has been determined that horizontal tubes are always connected to vertical tubes, but it is not sure if this connection is made always in the same side – left or right - for each vertical plane (Figure 12). This aspect is really difficult to control on site, so it will be analyzed how this parameter affects the results obtained (Table 7).

(01): Horizontal tubes at left side of vertical tubes.
(02): Horizontal tubes at right side of vertical tubes.
(03): Horizontal tubes at both sides of vertical tubes.

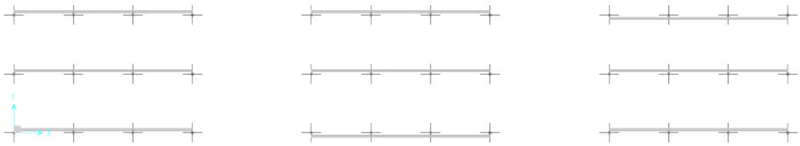

Figure 12: Different positions considered for eccentricities between horizontal and vertical tubes. Top view (OXY).

Table 7: Comparison between different positions considered for eccentricities between horizontal and vertical tubes.

STATIC LINEAR ANALYSIS (D*1'35 + W*1'5) Offset + Rigid joints		
	Displacement OY (Joint 85) (m)	Axial Force (Frame 1) (KN)
Model 01	0'00541	12'95500
Model 02	0'00544	12'43400
Model 03	0'00543	13'28600

4 Application to Seville fair gateways

The solution currently adopted for the numerical analysis of Seville Fair gateways was a solution with released joints and no eccentricities, but the truth is that this solution does not correspond to the real construction model, since essentially eccentricities do really exist and they should be considered for proper analysis [7].

To solve this problem without modeling eccentricities it could have been chosen to introduce a bending moment equal to the axial force multiplied by the distance to the tube axis, but this solution will also complicate the calculation process, so that finally the solution adopted is to penalize the maximum permissible compression load when performing the dimensioning process. Moreover, from the point of the dimensioning process, there is a factor that keeps this analysis on the side of safety: considering released joints when in fact couplers don't allow totally free rotations means that tubes are dimensioned for a higher bending moment than the real one, so that somehow, the penalty for eccentricities is being compensated.

From the point of view of the dimensioning process for the structure [8], this solution could be adopted as valid, but nevertheless, with this solution the deformability of the global model introduced by eccentricities that has been demonstrated is not being considered. Therefore, it is necessary to compare the actual analysis model for Fair gateways solved without eccentricities and released joints against another analysis model in which eccentricities are considered as well as stiffness values extrapolated from the above analysis.

Table 8: Seville Fair gateway 2011. Consideration or not of eccentricities, and adoption of different stiffness values.

	No offset + Released joints	Offset + Rigid joints	Offset + Elastic joints
Fundamental period T1 (s)	0’4631	0’4746	0’4750
Displacement OY (m)	0’1325	0’1355	0’1356

Axial efforts obtained for each analysis model at vertical tubes corresponding to the front plane subjected to compression stress are also compared (Figure 13), and it is noted that the results obtained in the second and third proposal are virtually identical, and differ somewhat with respect to the first proposal.

(01): No offset + Released joints.
(02): Offset + Rigid joints.
(03): Offset + Elastic joints.

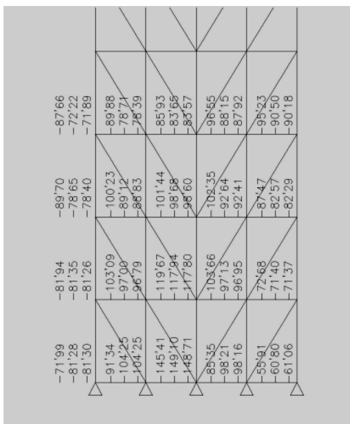

Figure 13: Seville fair gateway 2011. Front view (OXZ). Axial efforts (KN).

5 Conclusions

It is noted that not considering eccentricities, there is no significant difference between rigid, released or elastic joints. This is due to diagonalization in each and every face of the prismatic module.

It finds that considering eccentricities, there are important differences between considering rigid joints or released / elastic joints.

There are differences, not very significant, depending on the randomness of the position of the eccentricity between the tubular elements.

It is a fact that eccentricities do exist in the real model. After comparing the results obtained in different models considering or not these eccentricities, it is noted that the results obtained are slightly different. Therefore, taking account these differences, the analysis model should consider these eccentricities.

However, it must be considered that tubular elements are not really unitary as in the analysis model discussed so far, but in fact each tubular element must have an analysis section equivalent to the real number of elements obtained after dimensioning the structure. Each one of these elements will have a different eccentricity, so it should not be assigned a single value to the equivalent fictitious element. From this point of view, it is difficult to consider eccentricities as occurring in the real model.

With regard to the joint stiffness, it is true that upon consideration of eccentricities, using stiffness values extrapolated from the referenced test it is possible to obtain very similar results to those obtained with rigid joints. Certainly, actual values of stiffness are unknown, so the best option is to work with rigid joints considering that, with samples of material available, it seems indeed that rotations are practically prevented around any of three local axes of the tubular element, so these values should be close to the real ones, or at least, be of the same order of magnitude.

Finally, it is important to remark that while we are considering eccentricities, we are ignoring the presence of couplers at the level of structural self-weight, which, given the large number of elements to provide, can to be influential. That is why when generating load combinations self-weight should be increased in approximately 50%, so that in this way the existence of the couplers is considered.

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