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On the steel cost of circular flat-bottomed silos designed using the Eurocodes

Carlos González-Montellano†, Álvaro Ramírez‡, Eutiquio Gallego‡† and Francisco Ayuga‡‡

BIPREE Research Group (Buildings, Infrastructures and Projects for Rural and Environmental Engineering). Universidad Politécnica de Madrid. Avda. Complutense S/N, 28040 Madrid. Spain

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Abstract. Nowadays, Eurocodes have become the reference standards for silo design within the European Union. They include new procedures for load assessment and structural verifications aiming to design safer silos. However, many silo manufacturers are still reluctant to use them (or at least all their prescriptions) because of the loss of competitiveness they are experiencing in comparison with former standards. This paper shows how steel cost of flat-bottomed circular silos varies when different silo geometries and stored materials are considered. The influence of critical structural verifications on steel costs, such as buckling of the silo wall, were also analyzed and some conclusions and practical recommendations for silo designers were proposed.

Keywords: Eurocodes; silo; costs; steel; buckling.

1. Introduction

Steel silos are storage structures widely used nowadays in farms, food and pharmaceutical industries. Therefore, manufacturers are usually interested in minimizing the amount of steel used in their construction. Different silo design codes have been followed until now in the European countries such as those provided by the Deutsches Institut für Normung (DIN) in Germany or the Association Française de Normalisation (AFNOR) in France. However, the Eurocodes by the European Committee for Standardization (CEN) are nowadays being adopted as reference standards for silo design in Europe (Rotter 1998, 2001, Vidal *et al.* 2005).

Eurocode EN 1991-4 prescribes load cases regarding the stored material within silos and their geometry. Considering the particular case of a circular flat-bottomed silo, pressure distributions are basically dependent on the mechanical properties of the stored material (Moya *et al.* 2002, 2006) such as the bulk unit weight (γ), wall friction coefficient (μ) or lateral pressure ratio (K) and silo geometries: diameter (d_c) and height (h_c) or capacity (Q) and slenderness ($\lambda = h_c/d_c$).

Eurocode EN 1993 4-1 proposes procedures for the design of steel silo structures: structural

† Researcher, Corresponding author, E-mail: carlos.gonzalez.montellano@upm.es
‡ Associate Professor, E-mail: alvaro.ramirez@upm.es
‡† Associate Professor, E-mail: eutiquio.gallego@upm.es
‡‡ Professor, E-mail: francisco.ayuga@upm.es

verifications for silo walls, hoppers and singular elements (ring girders, roofs, lateral openings…). The structural verifications given in this standard basically involve comparisons between forces acting in every structural element and the resistance of those elements to different failure modes. Those resistances will take into account the particular geometry and material of these elements as well as their distribution in the silo wall.

When a silo installation is planned, some factors are usually fixed by the activity of the industry, such as the bulk solid, the required capacity, the type of silo wall; steel, concrete, etc… However, geometries are open to discussion. Efficient designs involve taking decisions among several possible geometrical configurations. For instance, a same capacity could be achieved by using either an individual big silo or a group of small silos. Furthermore, no matter what the solution is, different slenderness can be adopted for every individual silo. Therefore, there are multiple solutions and each one will have different steel costs.

As a consequence of the interest of some Spanish manufactures in optimizing their manufacturing process, a program to automate the design of silos according to the Eurocodes and other silo codes was developed by BIPREE (Buildings, Infrastructures and Projects for Rural and Environmental Engineering) research group. This program was used in this research work to carry out an analysis of the steel cost involved in several designs of silos. The aim of the present work is to analyze the amount of steel required to manufacture a circular steel flat-bottomed silo when several geometries are presented and comparing solutions using different stored materials. Furthermore, the influence on steel costs of some critical verifications, such us buckling, is also analyzed.

2. Materials and methods

2.1 Silo elements: body sheets and stiffeners

Silos considered for this research work were circular, flat-bottomed and designed for concentric filling and discharge. Vertical walls were composed with corrugated and rectangular body sheets made of galvanized steel. These walls were reinforced by stiffeners made of the same material. Stiffeners were vertically placed along several generatrixes of the cylinder regularly spaced. As per EN 1993-4-1 (5.3.4.3.4 (b)), the stiffeners will assume all vertical loads transmitted through the wall, while the body sheets will assume those forces derived from horizontal loads.

For design purposes, the silo is divided into N levels and all body sheets that compose a level will have the same thickness. Regarding stiffeners, the same dimensions will be kept for every two consecutive levels (Fig. 1).

Following is presented the description of the aforementioned elements (body sheets and stiffeners):

- **Body sheets:** Bended rectangular pieces of corrugated steel, 1.140 mm effective height and 1.250 mm developed length. Every level i (i = 1, 2, 3, ..., N) in the silo will be composed of a single row of body sheets, existing as many body sheets as necessary to complete the whole periphery at each level (approximately, the number of body sheets in every level is about $1{,}3 \cdot d_c$). Bolted joints of size M10 will be used to join body sheets.

  Corrugated profile of body sheets (Fig. 2) is defined as 76 mm wavelength (W), 31.6 mm curvature (R) at the crest and 74º amplitude (θ).

  Gross area of the vertical cross-section of a body sheet is given by $1250 \cdot t$, where "t" is the

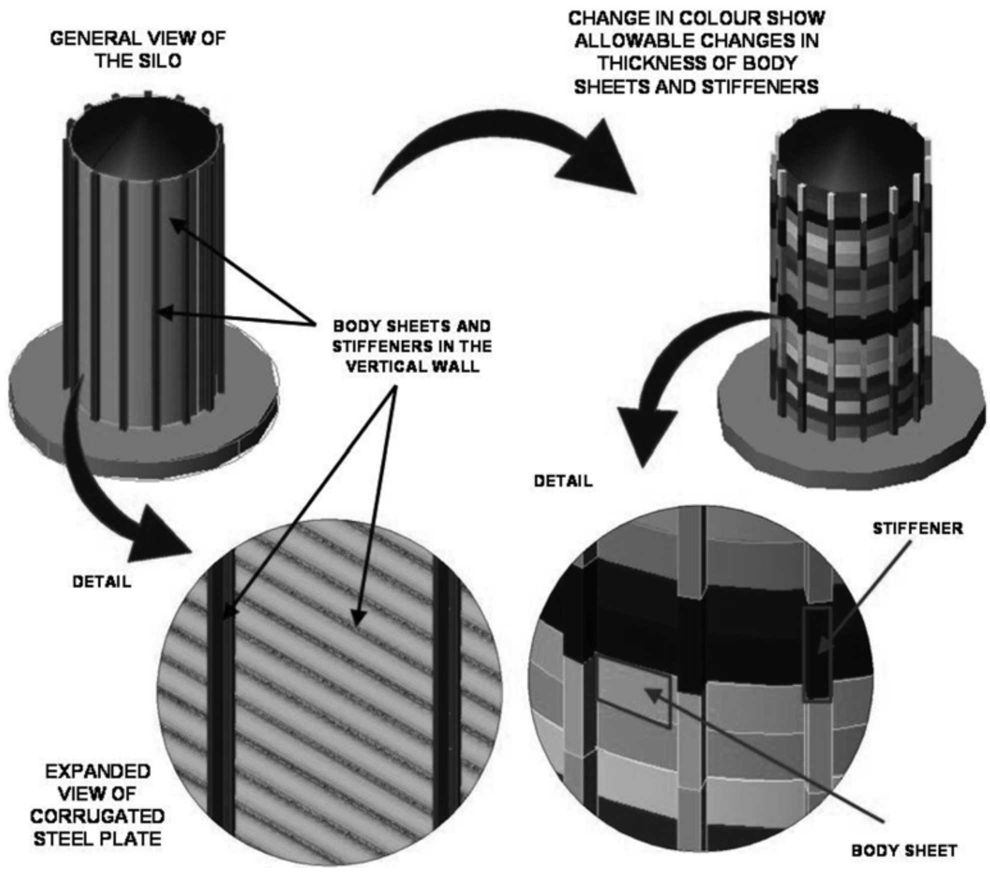

Fig. 1 General view of silos studied

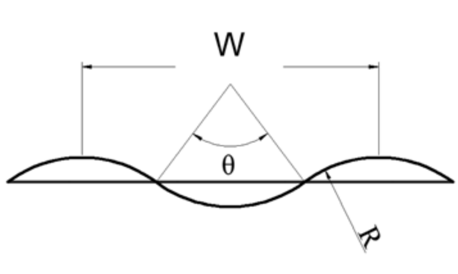

Fig. 2 Corrugated profile of body sheets

thickness of the sheet, selected from the following series: 0,8-1-1,5-1,6-1,8-2-2.4-2.5-3-3.6-4-5-6-7.5-9 mm. Net area of this cross-section will be taken as the gross area less appropriate deductions for holes made in the lateral joints between body sheets. These joints have an appropriate composition so that their resistance is similar to the one of the net area of the body sheet in which they are used.

The yield strength (f_y) and the ultimate strength (f_u) of the galvanized steel used in body sheets is 343 N/mm^2 and 420 N/mm^2 respectively.

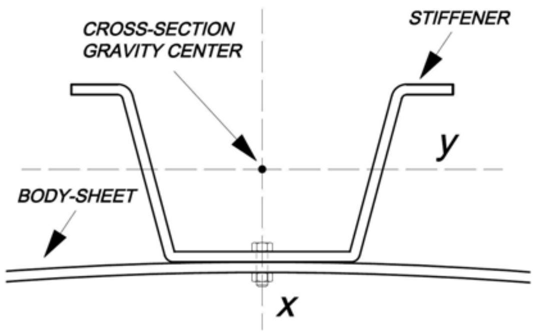

Fig. 3 Sketch of stiffeners

Table 1 Mechanical properties of the cross-section of the stiffeners

t (mm)	I_y (mm^4)	A_{eff} (mm^2)[1]
1,5	234.156	290,7
2	312.609	456,7
2,5	391.290	567,0
3	470.296	675,0
3,5	549.401	781,9
4	628.811	886,4

1) According to EN 1993-5.

- **Stiffeners:** The vertical wall of the silo is reinforced by means of vertical stiffeners, made of the same material as the body sheets, and spaced at a constant distance of d_r = 800 mm around the silo wall. They are fixed to the wall by using M10 bolts.
  Stiffeners are cold formed steel profiles with an omega-like cross-section (Fig. 3). The stiffener placed at a particular generatrix is formed by joining different pieces every two levels of the silo wall (See Fig. 1). These pieces, named individual stiffeners, can take one of these single thicknesses (t (mm)): 1,5-2-2,5-3-3,5-4 depending on their position on the silo wall. When necessary, thicker stiffeners could be achieved by combining two or more single thickness profiles.
  Mechanical properties of cross-section of stiffeners of single thickness are shown in Table 1, having all of them a developed length of 237 mm.
  An overlapping piece is placed between two consecutive individual stiffeners of the same generatix in order to ensure a good transmission of the force in the contact between them. These overlapping pieces are made of the same material and shape as the stiffeners.

2.2 Silo design: Loads and structural verifications

Only loads due to the stored material and self-weight of the elements that compose the silo will be considered in the design. In this way, conclusions obtained from this study will be independent of a particular location of the silo (since no wind, snow or seismic actions are considered) or a particular installation (no machinery, catwalk or similar loads have been considered).

Loads exerted by the stored material within the silo are obtained by using the Eurocode EN 1991-4. All geometries and stored material selected for the silos analyzed (Section 2.3) allow adopting the simplified procedure given in EN 1991-4 (5.2.3) for the patch load consideration.

The aforementioned actions, in accordance with the principles of load assumption stated in 2.1, cause the following internal forces in the structural elements of the silo:

- **Body sheets.** The vertical cross-section of a body sheet is considered to be subjected to a uniform tensile force calculated through the value of the horizontal pressure at the lower height of this body sheet. The horizontal pressure considered at that point will be the higher between horizontal pressures for filling and discharge (incremented by patch load consideration when necessary).

  Eq. (1) gives the uniform tensile force (T_i) present in a body sheet of a generic level i

$$T_i = [p_h]_i \cdot \frac{d_c}{2} \cdot EHS \tag{1}$$

  Where d_c is the silo diameter, EHS is the effective height of a body sheet and $[p_h]_i$ is the horizontal pressure at the lower height of the level.

- **Stiffeners.** Each stiffener is considered to be subjected to a uniform compressive force determined as the sum of:
  - Compression due to the wall frictional traction on the vertical wall. Let be $[F_w]_i$ the value of the vertical compressive force per unit length of silo perimeter (kN/m) at the height of the lower point of the level i. Its value is calculated integrating the wall frictional traction on the vertical wall (p_w) between that point and the origin of coordinates (Eq. (2)).

$$[F_w]_i = \int_0^i p_w(z)dz \tag{2}$$

    The compressive force in an individual stiffener (N_w) is calculated multiplying the previous value of $[F_w]_i$ by the circumferential separation between stiffeners (d_r).
  - Compression due to the self-weight of structural elements of the silo. Let be $P_{ST,i}$ the self-weight of a individual stiffener at the level i, $P_{OV,i}$ the self-weight of the possible overlap at the level i and $P_{S,i}$ the self-weight of all body sheets at level i divided by the number of vertical stiffeners in the silo. The compressive force acting on a individual stiffener at level i ($N_{SF,i}$) due to the self-weight of the stiffeners, overlaps and body sheets in this level and above is obtained using Eq. (3)

$$N_{SF} = \sum_1^i P_{ST,i} + P_{OV,i} + P_{S,i} \tag{3}$$

The assessment of the resistance of every structural element in the silo has been carried out according to the Eurocodes EN 1993 1-1, EN 1993 1-8 and EN 1993 4-1.

Regarding body sheets, resistance verification involves the selection of its thickness so that its strength is higher than the tensile force acting on it (T_i). That strength will be the least of the tension resistance of the body sheet net area and the resistance of the joint between body sheets of the same level (considering shear and bearing resistances).

The structural verification of the stiffeners will follow the methodology given in EN 1993-4-1

(5.3.4.3.4 (b)). Thus, it should be verified that the compressive force acting on them ($N_w + N_{SF}$) is lower than the resistance to concentric compression of the effective cross-section of the stiffener and the critical buckling resistance of the stiffener, allowing for the stiffness of the sheeting in resisting buckling displacements normal to the wall (EN 1993 4-1 (5.3.4.3.4)).

The later resistance for stiffeners is not only dependent on the particular mechanical properties of the stiffeners but also of the body sheets mechanical properties. Because of that, when the limiting verification at a particular level i is buckling resistance, fulfilment of this verification can be achieved by increasing either the thickness of the stiffener or the thickness of the body sheets at that level i, or both at the same time. The strategy to be followed in each particular level i would be to minimize the amount of steel required.

2.3 Particular characteristics of studied silos

In order to consider the influence of geometric properties in the silo design, five discrete capacities (150, 500, 2000, 4000 and 6000 m^3) have been selected, considering for each one a wide range of different slenderness ratios (Table 2). To study real situations, the values of slenderness were chosen from the values presented in a commercial catalogue of a company working on silo manufacturing for every capacity considered.

On the other hand, to take into account the effects of the stored material, all geometries previously stated will be designed for six different materials: barley, sugar, flour, sand, limestone powder and phosphate. These materials have been selected according to their properties (γ, μ, K) so that a wide range of materials was considered. The values of the material mechanical properties (Table 3) were taken from the silo Eurocode EN 1991-4 and, in the particular case of the wall friction coefficient (μ), its value has been calculated using the Eq. (4):

Table 2 Slenderness values considered in each silo capacity

Capacity (m^3)				
150	500	2000	4000	6000
6.962	6.317	4.329	3.407	2.775
4.356	3.957	3.343	2.825	2.557
2.104	2.738	2.647	1.946	2.136
1.400	1.781	2.146	1.693	1.614
0.869	1.322	1.715	1.465	1.419
0.619	0.936	1.427	1.072	1.240
	0.741	0.951	0.965	0.983
	0.466	0.829	0.868	0.814
		0.718	0.696	0.739
		0.529	0.548	0.669
		0.511	0.482	0.603
		0.432		0.541
				0.473

Table 3 Mechanical properties of the materials considered

Material	γ (kN/m^3)	μ	K
Barley	8	0,49	0,59
Sugar	9,5	0,6	0,5
Sand	16	0,68	0,45
Limestone powder	13	0,56	0,54
Flour	7	0,79	0,36
Phosphate	22	0,54	0,56

$$\mu = 0,8 \cdot \tan\phi_i + 0,2 \cdot \mu(D2) \tag{4}$$

Where $Ø_i$ is the angle of internal friction and μ (D2) is the wall friction coefficient for a wall surface category D2 according to EN 1991-4.

Every particular silo design could be summarized through the total amount of steel required (kg) per every cubic meter of capacity (kg/m^3). This ratio is indicative of the efficiency in the use of the material and will allow comparing between different geometries and materials.

Furthermore, for a better understanding about how the total steel cost (kg/m^3) varies in relation to the variables studied, it will be considered its breakdown in the amount of steel used in the two structural elements of the silo: body sheets and stiffeners.

Finally, aiming to observe the influence of the buckling resistance verification on total steel cost, every silo design will be carried out in two ways. The first one will consider all verifications stated in section 2.2 (Design considering buckling) while the second one will omit the buckling resistance verification in the stiffeners (Design without considering buckling).

3. Results and discussion

Graphs in Figs. 4 and 5 show the results obtained from all designs analyzed in this research work. Each figure is structured in columns, containing the following information:

· Total steel cost (kg/m^3) as function of the slenderness and the capacity when a *design considering buckling* has been carried out.
· Total steel cost (kg/m^3) as function of the slenderness and the capacity when a *design without considering buckling* has been carried out.
· Difference of total steel cost (kg/m^3) between the two types of design considered, as a function of the slenderness and the capacity and for all materials studied

3.1 Results in design considering buckling.

When considering design with buckling, it can be observed (Figs. 4(a) and 5(a)) how, no matter what material or capacity of the silo is, the total steel cost always increases with the slenderness, being that relation almost linear.

There are not big differences in steel cost between capacities when the slenderness is lower than $\lambda < 1$, showing that there is not a significant influence of the scale factor in its design (specially in

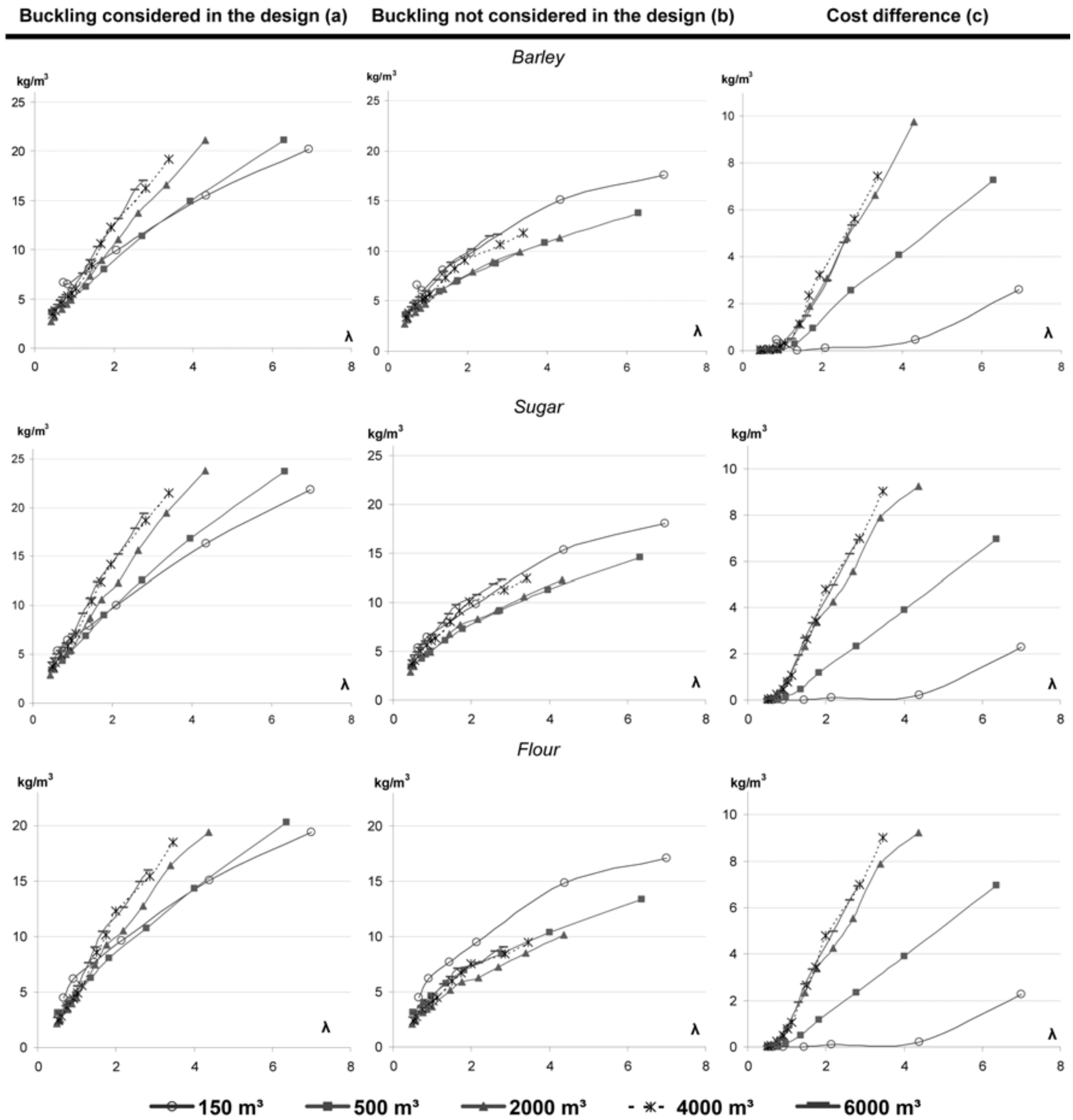

Fig. 4 Total steel cost (kg/m^3) as a function of slenderness (λ) and silo capacity (m^3) for materials barley, sugar and flour and for the design types considered: with buckling and without buckling

barley, sugar and flour). However, it is slightly appreciated a better efficiency in the use of material in intermediate capacities (500-2000 m^3) when the material is barley, sugar or flour, while lower capacities are more efficient in the rest of materials (whose mechanical properties take higher values).

When the slenderness (λ) is more than 1, there are more differences among capacities and always the amount of steel increases when the capacity of the silo grows up. However, these differences do not exist when very high capacities are considered (4000-6000 m^3), not having, again, a significant

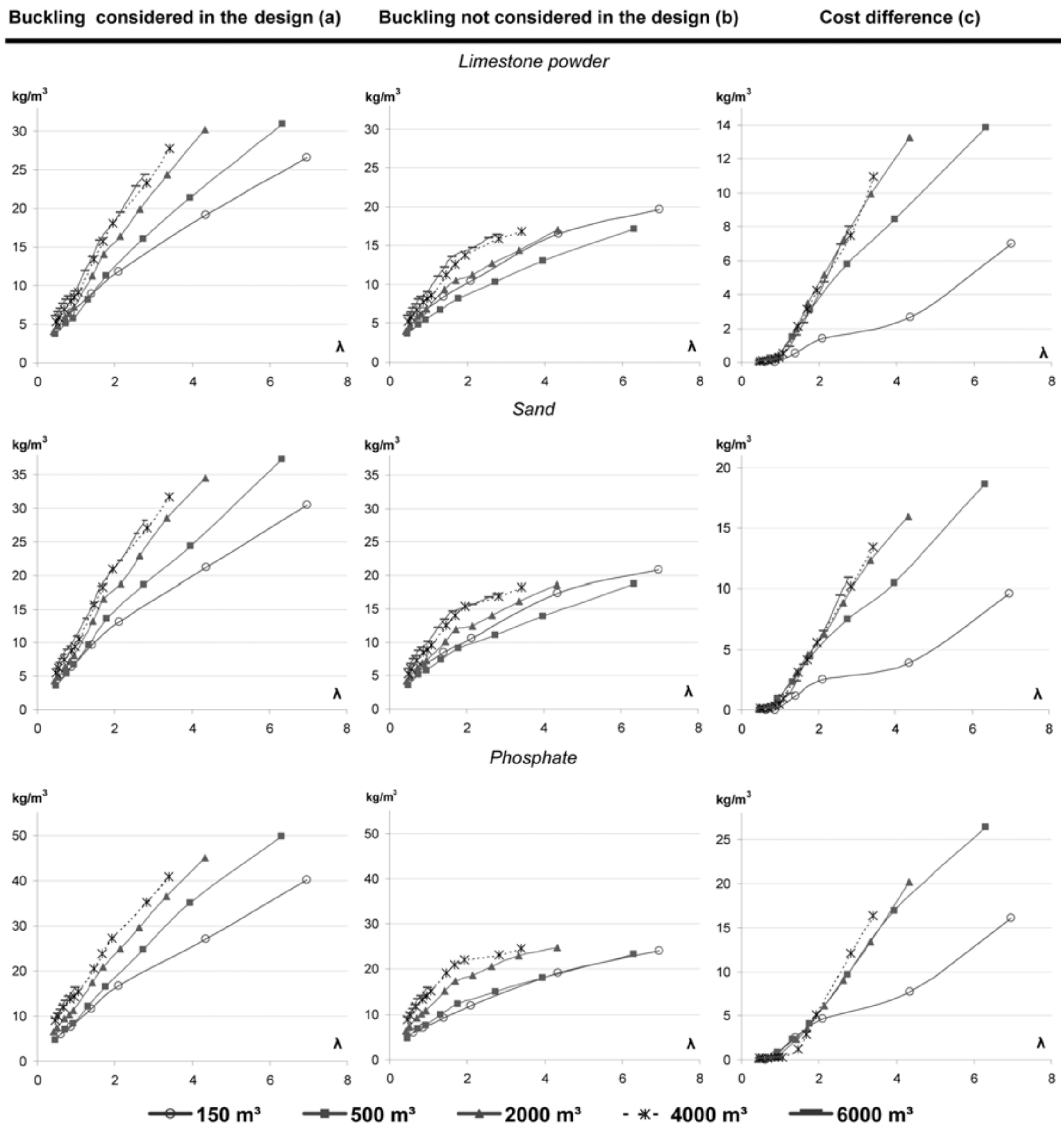

Fig. 5 Total steel cost (kg/m^3) as a function of slenderness (λ) and silo capacity (m^3) for materials limestone powder, sand and phosphate and for the design types considered: with buckling and without buckling

influence of the scale factor in the design.

There are differences in the steel costs of the silos when considering the same slenderness and capacity for different materials. This means that the increasing and linear relation between steel cost and slenderness takes different slopes depending on the material considered. There is a same material hierarchy, independently of the capacity and slenderness, when considering their total steel cost: flour, barley, sugar, limestone, powder, sand and phosphate.

3.2 Results in design without buckling

Figs. 4(b) and 5(b) show how the total steel cost is still increasing in relation with the slenderness for all capacities and materials. However, in this case, the relation is not clearly linear, decreasing the rate of growing as the slenderness takes higher values.

Furthermore, differences between capacities, for a specific material and slenderness, are not as important as in a design considering buckling. Besides, with a design without considering buckling and for all values of slenderness, the steel cost is not always higher when the capacity grows, being intermediate capacities (500 and 2000 m^3) more efficient when the stored material is barley, sugar or flour, while lower capacities (150 m^3) are more suitable in other materials (those whose mechanical properties take higher values).

3.3 Comparison of types of design

Differences between both types of design (Figs. 4(c) and 5(c)) show the increment in material required to fulfil the buckling resistance verification. That increment is not significant when slenderness (λ) is lower than 1. That is because buckling resistance verification in the stiffeners is less limiting than the resistance to uniform compression of the effective cross-section of these stiffeners. However, for elevated slenderness, the aforementioned increment is well seen, taking higher values as the slenderness grows.

These increments became more important in intermediate-high capacities (2000-4000-6000 m^3) without many differences between them. In low capacities (150-500 m^3) differences between two types of design are not so important. In fact, for the lower capacity (150 m^3) and for those materials whose mechanical properties take lower values (barley, sugar and flour), there is no increment until slenderness (λ) is 3-4 (instead of $\lambda = 1$ for intermediate-high capacities)

Quantitatively, increments in steel cost due to bucking consideration can take important values, even doubling the steel cost when slenderness (λ) goes beyond 2.5-3 in silos with intermediate-high capacities (2000-4000-6000 m^3).

These differences between both types of design are due to the increments in thickness applied in body sheets and stiffeners to satisfy buckling verification. Fig. 6 shows a comparative between the steel cost in body sheets and stiffeners (kg/m^3) as a function of the slenderness and capacity for the material barley.

Steel cost in body sheets, when buckling is not considered, increases with the slenderness at first, but for elevated values of this later variable becomes constant (in low capacities, 150-500 m^3) or even decreases (in intermediate-high capacities). But in a design considering buckling, where buckling is taken into account, it is necessary to increase body sheet thicknesses, particularly at elevated slenderness, to satisfy buckling verification. That is why the aforementioned attenuations disappear in a design considering buckling, always keeping an increasing tendency of the steel cost in body sheets with the slenderness.

Steel cost in stiffeners, for both types of design, always grows with slenderness, showing a quite clear linear tendency. However, when buckling is not considered, that linear evolution has a lower slope, resulting in a smaller steel cost in stiffeners for a same capacity and slenderness. When buckling is taken into account, the steel cost in stiffeners increases because in one or several levels in the silo stiffener thicknesses have been incremented to satisfy buckling verification.

As already stated, the strategy followed to decide particular values of thickness increments in

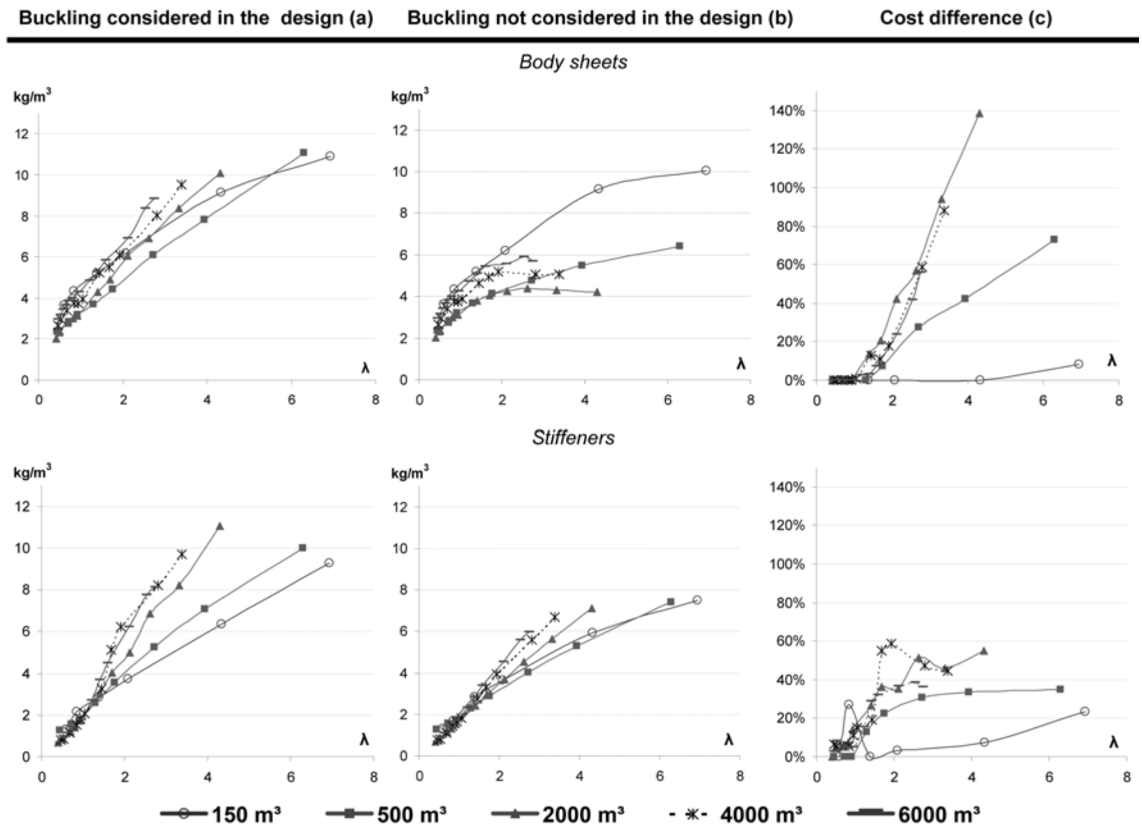

Fig. 6 Total steel cost (kg/m^3) in body sheets and in stiffeners as a function of slenderness (λ) and silo capacity (m^3) for material barley and for the design types considered: with buckling and without buckling. Relative difference (%)

body sheets and/or in stiffeners to fulfil the buckling verifications at each level is minimizing the total steel cost at that height. It can be observed when comparing the increments of steel cost in body sheets and stiffeners (Fig. 6(c)) that relative increment (%) in the first one is notably higher than in second. That shows that, in general, it is more effective to increment thicknesses in body sheets than in stiffeners.

4. Conclusions

Some practical recommendations useful to the silo designer when establishing design parameters involved in the storage installation project have been presented.

Total steel costs of a storage installation are not only related to the higher o lower cost of the steel required to manufacture the silo or battery of silos needed. There are many other factors, such as the cost of the occupied place, the foundation or the transport machinery used for the filling and discharge of silos, whose influence is not negligible at all. It is therefore necessary that the designer takes into account all factors involved and, in this consideration, the present work intend to show to the designer how one of these factors, the steel cost of the silo, behaves.

Assuming that designers must consider all dispositions of Eurocodes and they have as objective the project of a storage installation with a certain capacity for a particular material, it can be stated that the most economic way to achieve it is through silos as less slender as possible, no matter what the capacity or the material are.

If the properties of the material to be stored are similar to those of barley, sugar or flavour and the slenderness of the silo is $\lambda \leq 1$, it will be more efficient to use silos of intermediate capacities (500-2000 m^3) instead of silos of very small or very high capacity. The use of a silo battery or a unique silo to reach the whole capacity will depend on the relative values of this whole capacity and those capacities indicated as more efficient. If the material is similar to sand, limestone powder or phosphate (i.e., materials with high values of their mechanical properties), it is recommended to use silos as small as possible and, because of that, it is always preferred a battery of silos in front of a single silo with the whole capacity required.

If the silo has a slenderness up from $\lambda = 1$, geometric parameters must be fixed in such a way that the final slenderness is as close as possible to $\lambda = 1$, no matter the capacity or material are needed, because, as stated in section 3, the total steel cost always increases with the slenderness.

If all provisions of Eurocodes must be accomplished and the limiting verification is that related to the buckling of the wall *(*$\lambda > 1$), it is recommended to follow a technique of minimizing the amount of steel required when deciding the values of the increments to be applied in body sheets and stiffeners to fulfil the buckling verification. Although for a particular level in the silo it may be better to increase the thickness in the stiffener rather than in the body sheets, in general, it is more efficient to increment thicknesses in the body sheets, no matter what geometry or stored material are considered.

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