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Publication date:
2012

Document Version
Early version, also known as pre-print

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Abstract

Silos are subject to several types of actions or loads. In the current Eurocode, EN 1991-4 (2006) [3] , the following are listed: loads from the stored material, wind loads, snow loads, imposed loads and deformations, thermal loads, seismic loads, and loads from dust explosions.

In the practical design of a silo, these actions must be combined according to the rules in EN 1990 (2002) [2], which implies that a series of design situations must be considered and the corresponding combination of actions selected, generally with a principal load and accompanying loads. Finally, each accompanying load must be scaled to a value that accounts for the reduced probability of simultaneous occurrence of the combined actions. This scaling factor is described as the load combination factor.

When compared with similar developments of combination factors for other types of structure, silos present some significant additional challenges. A first concern is that the key features that must be considered in design depend on the expected mode of failure of the structure. The actions and their combinations must be defined in such a way as to address the critical stress states in the structure that can cause failure modes by shell bending or by shell buckling. As a result, different load combinations are needed for different types of silos (concrete or metal, squat or slender etc.) and for silos designed for different operating conditions (flow pattern, method of discharge etc.). Apart from understanding the nature of loads on silos, this aspect calls for an acute awareness of the structural consequences of each load and a clear understanding of the safety philosophy. A second concern relates to seismic loads, where there must be a division between on-ground and elevated structures, since the seismic response is completely different (Trahair et al., 1983) [7], and different degrees of partial filling can be critical for an elevated silo. Further, both the properties of the stored solid and the operating conditions impact on many aspects of the statistical assessment required to define load combination factors in a rational manner.

In two annexes of the current EN 1991-4 (2006) [3], load combinations and combination factors are prescribed. However, they do not account for the differentiations described above and these annexes were developed before several of the other silo relevant actions had even been defined in the relevant Eurocode.

The paper discusses the current rules for load combinations in EN 1991-4 (2006) [3] and offers some suggestions for amended rules to address these and other issues.

Key words: Silo, Loads, Load Combinations, Design, Standard

1. Introduction

Silos are subject to several types of actions or loads. In the current Eurocode, EN 1991-4 (2006) [3], the following are listed: loads from the stored material, wind loads, snow loads, imposed loads and deformations, thermal loads, seismic loads, and loads from dust explosions.

In the practical design of a silo, these actions must be combined according to the rules in EN 1990 (2002) [2], which implies that a series of design situations must be considered and the corresponding combination of actions selected for each, generally with a principal load and accompanying loads. Finally, each accompanying load must be scaled to a value that accounts for the reduced probability of simultaneous occurrence of the combined actions. This scaling factor is described as the load combination factor.

It is a general principle in the European structural standards, the Eurocodes, that the three items: safety considerations, the specification of loads, and the design of structures, may be considered independently of each other. This means that safety considerations, as defined in EN 1990 (2002) [2], are valid for all types of loads and all types of structures made of different materials (concrete, steel, aluminium, timber etc.) and that the loads specified in the action standards are valid for all types of structure.

When it comes to the practical design of silos, this philosophy is challenged for at least three reasons. Firstly, the structural response to different load conditions is different for different types of silo. Typically, the ultimate limit state for a concrete silo involves shell bending as the failure mechanism, but in steel silos shell buckling is the commonest failure mode. Secondly, silos are used for different purposes with very different operating conditions. Typically, chemical process silos are run continuously whilst storage silos may be used to store materials only for a short period each year. This also implies that very different sizes and shapes are economic for different applications. Thirdly, the extreme load from a stored material is likely to occur on a large part of the structure every time a full silo is subject to discharge, and this extreme discharge load may be locked in if discharge is arrested before it is complete, potentially making the extreme discharge load persistent rather than intermittent.

The general rules for the combination of loads are prescribed in EN 1990 (2002) [2], but load combinations and the values of combination factors are temporarily prescribed in two annexes of the current EN 1991-4 (2006) [3] and are, according to the principle mentioned above, to be transferred to EN 1990 (2002) [2]. However, the current rules do not account for the differentiations described above and these annexes were developed before several of the silo relevant actions had even been defined in the relevant Eurocodes. Furthermore, the authors of this paper have not found any publication which provides a sound technical discussion of the considerations that should provide the basis for these rules for silos. Such a discussion is begun here, with a focus on the current rules for load combinations in EN 1991-4 (2006) [3] and some suggestions for amended or supplementary rules.

2. Combination rules

The general rules for verification of structures are prescribed in EN 1990 (2002) [2]:

"It shall be verified that, in all relevant design situations, no relevant limit state is exceeded when design values for actions or effects of actions and resistances are used in the design models." It is required that the individual actions should be combined to form critical load cases. *"However actions that cannot occur simultaneously, for example due to physical reasons, should not be considered together in combination."*

The rule for load combinations says that each combination, a load case, shall include:

- All permanent actions
- A leading variable or accidental action (typically giving a name to the load case)
- Actions which have some probability of occurring simultaneously, termed accompanying actions, each with its magnitude reduced by the load combination factor, ψ.

Specific rules for the verification of ultimate limit states and for serviceability limit states are prescribed in detail in EN 1990 (2002) [2]. Different values of the combination factors are used in these rules. The following combination factors are relevant to the discussion below:

1. ψ_0 (Combination value) factors are chosen so that "*the probability that the load effects caused by the combination will be exceeded is approximately the same as that for the characteristic value of an individual action*."

   These factors are used in the ultimate limit design for persistent or transient design situations and for the serviceability limit state.

2. ψ_1 (Frequent value) factors are chosen "*so that either the total time, within the reference period, during which it is exceeded is only a small given part (typically 1%) of the reference period, or the frequency of it being exceeded is limited to a given value."*

   These factors are used in Accidental design situations.

3. ψ_2 (Quasi permanent value) factors are chosen "*so that either the total period of time for which it will be exceeded is a large fraction of the reference period (and typically approximately equal to the mean value of the load)."*

   These factors are used in accidental design situations, in seismic design situations and when evaluating the effect of differential settlements.

The combination rules and their corresponding factors are notionally based on Turkstra's rule with the Ferry-Borges-Castanheta load model [4] (ISO 2394,1998), which leads to the equations in EN 1990 (2002) Annex C [2]. This model is based on the assumption that the variable loads can approximated by a number of statistically independent realisations of equal time duration and that the annual maximum load can be modelled by a Gumbel distribution. The uncertainty of silo loads is dominated by model uncertainties and almost no statistics are available to determine either which statistical distribution is relevant or the magnitude of the variability. Thus current knowledge of silo loads cannot satisfy the assumptions that underlie the EN 1990 approach to load combination factors. Therefore currently the load combination factors can only be chosen by using engineering judgement based on knowledge of the structural behaviour of silos and the mode of their operation.

With a focus on ultimate limit states, this paper discusses which actions should be combined, and indicates appropriate magnitudes for the combination factors for different types and uses of silos.

3. Some characteristics of silos and their operation

As further background to the discussion, some characteristics of silos and their usage are described here. Further extensive information may be found in Brown and Nielsen (1998) [1].

3.1. The size of the silo

Silos are built in very different *sizes*. Some are small structures with a capacity below one tonne of stored particulate solid, while others are huge structures with capacities exceeding 10 000 tonnes. In the discussions undertaken during the development of EN 1991-4 (2006) [2] it was realized that a higher degree of rigour is necessary in the action assessment of larger silos. The following classification was therefore introduced:

1. *Action Assessment Class 1*, consisting of silos with a capacity in excess of 10 000 tonnes, or if there is a large eccentricity in the outlet, or the inlet in a squat silo, and the capacity is in excess of 1 000 tonnes.
2. *Action Assessment Class 2*, consisting of all silos not placed in another class.
3. *Action Assessment Class 3*, consisting of silos with capacity below 100 tonnes.

3.2. Silo structural behaviour

Some silos are thin walled shell structures carrying their loads predominantly by membrane stresses, with buckling in compression or through-thickness rupture of metal plate as the dominant modes of failure [4] (Rotter, 2001). These structures are typically made of steel,

aluminium or stainless steel. Other silos are relatively thick-walled shells in which slight asymmetries of loading lead to bending moments as a critical feature of the structural behaviour. These silos are typically made of reinforced concrete, but may also be made of other materials. A fuller discussion of this distinction is presented in Rotter et al. (1986) [5].

Because the response of the structure, and the ultimate limit state induced, are so different for these two types of silo, in drafting EN 1991-4 (2006) [3] it was decided that it is necessary to separate silos into two types: thick-walled and thin-walled. This decision permitted load models to be used that relate well to the critical loading conditions for the failure mechanism that is likely to be controlling in these circular shell structures (patch loads).

3.3. Geometries of silos

The relationship between the height and diameter (or horizontal characteristic dimension for non-circular silos) plays a major role in determining the loading on the silo walls, and this aspect is brought out in EN 1991-4 (2006) [3] through a rather complex separation of categories. The aspect ratio is termed the slenderness of the silo, with categories from very slender to squat and retaining geometries. Again, the ultimate limit states are very different in these different geometries, so that a load combination that is critical for one shape may be irrelevant or unlikely in another. Furthermore, a squat silo carries a considerable part of the weight of stored solids directly to the bottom, so that the scatter in the wall load is much smaller, leading to a small coefficient of variation in the definition of the load.

Furthermore, many silos are elevated. For these structures, much of the well-defined weight of the stored solid may be carried by a hopper, which is susceptible to quite different ultimate limit states. This situation suggests that a lower partial coefficient could be used for well-defined loads, but such a discussion is beyond the scope of this paper.

Silos constructed in either reinforced or prestressed concrete may be either single cylindrical vessels, or may be combined into interconnected batteries of silo cells to form a block that has very specific characteristics. In particular, load cases involving some filled cells and others empty, and conditions involving imposed deformations, need careful treatment in the consideration of load combinations. It is not clear how differentially filled cells can be incorporated into the load combination model without making special provision for batteries.

3.4. Operating conditions and usage

The mode of usage of the silo has a major impact on the loads and their probability of occurrence. The silo may be at an industrial plant, where it is being filled and discharged almost continuously and is rarely full and rarely empty, but no data will be available to the designer on this issue. Or it may be a grain silo that is filled once a year after the harvest and then emptied once a year. Or it may be at a harbour, where it is filled to capacity awaiting the arrival of a ship, at which point it is fully discharged and then filled progressively by trains arriving to refill it. The latter could have 10 fillings per year or 3 or 50. The designer is unlikely to know in advance. So silos are much more varied in usage than buildings or bridges, and the only way that this could be dealt with in choosing the load combination factor would be to have categories of usage relating to the number of expected filling and discharge cycles to be expected annually.

Further, the stored solid and the manner of operation may imply thermal actions from hot solids on filling, or additional air pressure which may have multiple causes: used as a discharge aid, or for homogenisation, or for control of moisture or temperature, or due to filling with fine grained solids that entrain interstitial air. These matters are crudely dealt with in EN 1991-4, but it may be more appropriate for them to be treated as load combinations.

4. Actions for load combinations

In the current Eurocode, EN 1991-4 (2006) [3], the following non-permanent actions are listed: filling loads from the stored material, discharge loads, imposed loads, wind loads (when the silo is full or empty), snow loads, imposed deformations: foundation settlements,

thermal action, seismic loads, and loads from dust explosions. Three accidental actions should be added to this list: impact and fire and actions during execution.

Some of these were discussed above. Here, three parts of the silo structure deserve separate recognition: the *top of the silo,* including the roof and any additional structure carrying conveyors etc., *the silo vessel,* involving vertical walls and hopper or bottom which are directly exposed to loads from the stored material, and the *substructure,* including the foundation which in many cases carries the total weight.

4.1. Filling and discharge loads

Filling and discharge loads have to be treated independently as two different loads because they may each cause the greatest load effects on different parts of the silo.

These loads are likely to occur with the characteristic value corresponding to the "full condition" as defined in EN 1991-4 (2006) [3] every time the silo is full or is being discharged from full. Because the discharge pressure state often persists after a partial discharge, it is necessary to include the discharge load as quasi-permanent, unless specific knowledge of the manner in which the silo will be operated dictates otherwise.

Thus, if the silo is used for storage most of the time, the duration of these extreme loads is much longer than that of other variable loads (e.g. wind loads), and they are therefore likely to occur simultaneously with other extreme loads. As a result, the combination value as well as the frequent value of the combination factor should be high. Given that the coefficient of variation of extreme loads in a silo is fairly small, a value of 0.8 or 0.9 could be chosen. However, these values are probably only relevant to silos that are used for long term storage, and not those in industrial applications where mean loads are lower. A further discussion should be held on the magnitude of the partial coefficient, which should perhaps be lower than 1.5, but such a discussion is again beyond the scope of this paper.

The stochastic variability associated with filling and discharge loads is mainly a problem for the design of the vertical walls of the silo because of the potential for redistribution of load between different parts of the wall and between the wall and the bottom. Under static conditions, the substructure carries a load that is much better defined.

The value of the quasi permanent combination factor depends on the manner in which the silo will be used and on the load case to be considered. Whilst the designer probably has much information on this when the design is undertaken, it is difficult to codify into EN 1990. If the design situation involves differential settlements and the silo is used intensively, the value might be around 0.8, but it might be only 0.2 for a silo that is used for shorter periods.

If the design situation is seismic, it seems inappropriate to use the quasi permanent combination factor as prescribed. The total mass of stored material at the time of the seismic event is relevant. If the silo is a grain silo, it is most likely that the silo is either full or empty, so that the partially full concept is not relevant, but if it is an industrial silo, it will usually be partially full, and its seismic response will be greatly affected by the level of filling. Thus it is difficult to define a proper value for this combination factor without having more specific information about the silo and its usage. It may be appropriate to take the combination value as the frequent value, but only for some applications. This discussion is relevant only to global horizontal excitations. Further challenges that need to be considered are a seismic action that affects the friction coefficient between the stored mass and the wall (potentially leading to significantly increased normal pressures), and vertical accelerations which can be overwhelmingly important for the substructure of elevated silos.

4.2. Wind loads

Wind is an important load for some silos. For the roof structure it plays the same role as in buildings. For the vertical walls, the critical situation in thin-walled structures is when the silo is empty, but the critical case for the substructure is always when the silo is full.

4.3. Imposed deformations

Imposed deformations may arise from foundation differential settlements, thermal action, or differential filling of connected silo cells in batteries. Because shell structures are highly indeterminate and lack ductility in some failure modes, imposed deformations usually induce stresses that must be considered, notably for the walls and substructure.

4.4. Thermal actions

Thermal actions may be climatic, as for other structures, but may also be caused by hot solids from industrial processes being placed in the silo. For silos, climatic thermal actions are rarely extreme, but thermal actions due to special operational conditions may occur at their full value every time the silo is filled, so the combination value should be 0.8 or 0.9. In some cases thermal actions may be relevant for the serviceability limit state only, but this discussion is again beyond the scope of this paper.

4.5. Accidental actions

Four accidental actions are relevant for silos:

Seismic action on silos has been noted above.

Design for *dust explosions* is relevant to silos that store solids susceptible to explosions. Such cases are best controlled by the design of venting openings [3] (EN 1991-4, 2006).

Vehicle impact is especially relevant to elevated silos that are supported on columns, where discharge is achieved by loading trucks that pass beneath the silo vessel.

Design for fire is generally not relevant for silos, though this situation is important for tanks that store highly combustible or explosive fluids.

5. Load cases

As noted above, each design situation is formulated as a load case involving all permanent actions, a leading variable action and relevant accompanying loads. The accompanying loads are scaled by the load combination factor.

For normal ultimate limit states (persistent or transient) the following combination factors are suggested here: filling loads (0.8 or 0.9), discharge loads (0.8 or 0.9), imposed loads (0.7), wind loads when the silo is full or empty (0.6), snow loads (0.5 or 0.7 – depending on the location and altitude of the site: EN 1990 (2002) [2]), imposed deformations: foundation differential settlements (1.0), thermal action - climatic (0.6) and thermal action from hot solids (0.8 or 0.9). Additional air pressure should be considered as specified in the design, with a higher value of air pressure being considered as accidental. For silo batteries, defined load cases for patterns of full and empty cells and imposed deformations must be devised and included in a revision of EN 1991-4. Filling loads and discharge loads cannot occur simultaneously, while the others may all occur at the same time. In load cases where the leading variable is not filling or discharge, filling loads should be disregarded and only discharge loads considered.

In applying the above principles, the following cases should be considered. To avoid repetition, the full list of accompanying loads is only given for the first case:

A. Filling load – in combination with imposed load (0.7) , wind loads (0.6), snow loads (0.5 or 0.7), imposed deformations: foundation settlements (1.0), thermal action - climatic (0.6) and thermal action from hot solids (0.8 or 0.9).

B. Discharge load - in combination with …..

C. Imposed load – in combination with discharge loads (0.8 or 0.9), ……..

D. Wind load – in combination with discharge load (0.8 or 0.9), ……

E. Wind load (empty silo) – in combination with imposed load (0.7), …. (If the presence of the stored solid is used in some structural design treatments to enhance the buckling strength or to restrain bending moments in silo walls, it is important that the ABSENCE of solid within the silo is specifically identified for this load combination).

F. Snow load – in combination with discharge loads (0.8 or 0.9), ……

G. Climatic thermal action – in combination with ……

6. Conclusions

This paper has presented a wide-ranging discussion of the many factors that affect the definition of load combinations for silo structures, with special reference to ultimate limit states. These structures are clearly identifiable as requiring considerably more information concerning the planned usage and operation of the silo to be available to the designer if load combination factors are to be based on rational decisions.

It is recommended that the load combinations to be considered for silos incorporate the following aspects:

1. Load combinations and combination factors should be set by dividing silos into different categories, at least according to the following:

   a) the relative thickness of the silo walls;

   b) the aspect ratio of the silo;

   c) whether the silo is on-ground or elevated;

   d) operating conditions.

2. The specific values of ψ factors can only be determined on the basis of engineering judgement at the present time.

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