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# REVIEW OF CURRENT TRENDS IN DESIGN OF WELDED STEEL TANKS FOR OIL STORAGE WITH FRANGIBLE ROOF TO SHELL JOINT

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## ABSTRACT

*As a safety measure, designs of welded steel tanks with fixed roof for oil storage may include selection of frangible roof-to-shell joint. This joint basically presents sacrificial joint in case of over-pressurization of tank interior. In addition, such joint has to fail before shell-to-bottom joint. Paper outlines trends in development of selection criteria for design of welded steel oil storage tanks with frangible roof-to-shell joint provided in design standards API 650 (American) and EN 14015 (European). Basic comparisons of American and European approach are outlined. In addition, some recommendation for further developments of design approaches are presented taking into consideration selection of welding technology.*

**Keywords:** frangible roof to shell joint, fixed roof storage tank, emergency venting

## 1. INTRODUCTION TO FRANGIBLE SHELL-TO-ROOF JOINT

Basic mean of temporary storage of oil products within oil refineries or storage (tank) farms are aboveground, vertical, cylindrical and steel welded storage tanks (hereafter, “tanks” only). According to internal pressure those tanks can be atmospheric (internal pressure <18 kPa), or low pressure tanks (internal pressure higher than 18 kPa, but less than 103 kPa) [1]. According to API (American Petroleum Institute), atmospheric tanks have to be designed according to API 650 norm, while low pressure tanks have to be designed according to API 620 norm. Design of storage tanks according to European norms is defined in EN 14015, while selection according to internal design pressure is a bit different [2].

One of the most important issues of safe operation of tanks with fixed roofs is venting. This is a consequence of internal pressure change due to normal or emergency working condition. Normal venting requirements are mostly fulfilled by use of safety-relief valves (pressure-vacuum relief valve) due to normal working condition. This is mostly due to filling and empting of tank for nominal pump rates. However, emergency venting may be required due to sudden increase of internal pressure. This is mostly a cause of external fire or even ignition of vapor (gaseous) phases inside tank when internal pressure can significantly increase with high rate. If tank is not equipped with emergency venting systems a collapse of tank structure is imminence, followed by catastrophic event. One of the safety measures that can be employed for emergency venting is so called “frangible roof-to-shell joint”. Such joint is practically sacrificial weld which has to collapse in event of excessive internal pressure, while shell-to-bottom joint has to be undamaged to provide structural and safe integrity of tank. Both design norms (American and European) for atmospheric storage tank, i.e. API 650 and EN 14015 provide design rules and selection criteria of frangible roof-to-shell joint.

This paper outlines basis of approaches for design and selection of storage tanks with frangible roof-to-shell joint according to API 650 and EN 14015 with some additional remarks for further development regarding welding technology.

## 2. DESIGN AND SELECTION CRITERIA FOR FRANGIBLE ROOF-TO-SHELL JOINT

The following table presents the basic parameters that have to be considered for selection of frangible roof-to-shell joint in accordance to API 650 and EN 14015.

*Table 1. The basic parameters and selection criteria of frangible roof-to-shell joint according to API 650 and EN 14015 [1,2]*

| # | Comparable parameters and selection criteria | | | |
|---|---|---|---|---|
| | According to API 650 | | According to EN 14015 | |
| | Parameter / Criteria | Par./Norm | Parameter / Criteria | Par./Norm |
| 1 | Tank diameter >15,25m or greater[1] | 3.10.2.6 | Tank diameter >5,00m and greater | K.1 |
| 2 | Slope of roof does not exceed 1:6 (max 9,5°) | 3.10.2.6 | Roof slope from 1:16 to 1:5 (from 3,5° to 11,3°) | K.1 |
| 3 | Fillet weld on shell-to-roof joint does not exceed 5mm (weld leg) | 3.10.2.6 | N/A | N/A |
| 4 | Limits to roof-to-shell joint detail | 3.10.2.6 and Fig. F-2 | Limits to roof-to-shell joint detail | K.1 and K.4 Fig. K.3 and K.4 |
| 5 | Maximum cross sectional area (A) on the roof-to-shell joint is limited | 3.10.2.6 | N/A | N/A |
| 6 | Unanchored tanks | F.1 | Unanchored tanks | K.1 |
| 7 | No welding or attaching to internal roof supported structure | 3.10.2.6 | No welding or attaching to internal roof supported structure | K.2 |
| 8 | Material for joint members:<br>No strictly proposed or defined, but assumed for joint failure pressure calculation (C-steel steel with yield stress 220 MPa) | F.6 | Material for joint members:<br>C or C-Mn steel with maximum allowable design strength (2/3 of yield stress) ≤260 MPa | K.3 |
| 9 | Failure pressure of roof-to-shell joint, $p_{FR}$ | F.1.2, F.4, F.6 | Failure pressure of roof-to-shell joint, $p_{FR}$ | K.4 |
| 10 | N/A | N/A | Failure pressure of bottom-to-shell joint, $p_{FB}$ | K.4 |
| 11 | N/A | N/A | Safe margin for difference between $p_{FR}$ and $p_{FB}$; i.e. must be[2]:<br>$p_{FB}>(2-3)*p_{FR}$ | K.4 |
| 12 | Design pressure and Maximum allowable design pressure -$p_{MAD}$,<br>Can be calculated if roof-to-shell joint cross sectional area is designed. Otherwise it can be specified by Purchaser | F.4.1, F.4.2 | Design pressure and Maximum allowable design pressure,<br>To be specified by Purchaser | 5.1, A.1 |
| 13 | Safe margin for difference between $p_{MAD}$ and $p_{FR}$:<br>$p_{MAD}<0,8*p_{FR}$ | F.4.3 | N/A | N/A |

1) Publication API Pub. 937 may permit selection of frangible joint for tanks extending minimum diameter below 15,25m

2) Safety coefficient 1-1,5 included in safe margin: $p_B$ 2-3 times greater than $p_R$

## 3. COMMENTS TO DESIGN AND SELECTION CRITERIA

### 3.1. Tank diameter

Selection of frangible roof-to-shell joint for smaller diameter tanks has to be taken carefully into consideration. While selection of frangible joint function well for large diameter tanks, small tanks designed to the API 650 rules have not always functioned as intended. However, if small diameter tank has to be designed with frangible roof-to-shell joint, it should be weaker than bottom-to-shell joint. Another important issue of frangible joint selection on small diameter tank is uplift due to increased internal pressure before roof-to-shell joint failure. Since uplift occurs for small tanks, this increases the possibility of shell-to-bottom joint failure [4]. However, API 650 and EN 14015 does not define or take into account any uplift influence of frangible roof-to-shell joint selection.

### 3.2. Fillet weld size on roof-to-shell joint

Weld leg size of roof-to-shell joint is limited only by API 650 to maximum 5 mm. It seems that all provided calculation in API 650 (design, maximum allowable and failure pressure) consider maximum weld leg size of 5mm. In addition, number of structural steel normative (e.g. EN 1993-1-8, DIN 18800) restrict minimum fillet weld throat thickness to 2-3mm (i.e. ~3-4mm leg size). However, due to frangibility requirements of weld, full strength weld joint in connection to parent material (weld of equal strength or stronger than parent material) must not be selected (Eurocode 3 – EN 1993 Part 1-8), whatever is thickness of parent metal. There are no any particular recommendations in API 650 and EN 14015 for welding technology, e.g. recommendations related to required mechanical properties of weld or $t_{8/5}$ concept for parent material welding.

### 3.3. Parent material of roof and upper shell course

Both normative suggest (or assume) use of weaker parent material (yield stress ≤220-355 MPa) of roof and upper shell course in comparison to bottom and lower bottom shell course. Simplified design selection of full strength bottom-to-shell joint should provide stronger joint as described in Par. 3.1. Therefore it seems that structural carbon steel S235JR (EN 10025) or ASTM A283 Gr.C is good choice for roof and upper shell course.

### 3.4. Design pressure, maximum allowable design pressure and failure pressure

While selecting frangible roof-to-shell joint it is the most important concern to predict failure pressure of designed roof-to-shell detail, particularly while taking into consideration fillet weld leg size. However, storage tank has to function properly while internal pressure is within normal limits of negative and positive design pressure (maximum allowable design pressure). Preliminary calculation of failure pressures (roof-to-shell joint) according to API 650 and EN 14015 approach show significant difference. However, tank designer has to reconsider and check any provided design pressure or maximum allowable design pressure by Client (or Purchaser) prior to selecting frangible roof-to-shell joint. Approach provided in API 650 (Par. F.4.1 and F.4.2), for determination of design pressure and maximum allowable design pressure according to already designed roof-to-shell joint seems to be reasonable.

Safe margin between failure pressure of roof-to-shell joint ($p_{FR}$) and maximum allowable design pressure ($p_{MAD}$) is another important concern. Simple comparison of requirements provided in API 650 and EN 14015 show some differences in approach. In paragraph F.4.3, API 650 require that $p_{MAD}<0{,}8*p_{FR}$. While taking into consideration reasonable requirement that $p_{MAD}$ has to be less than $p_{FR}$, in paragraph K.4, EN 14015 require that $p_{FB}>(2\text{-}3)p_{FR}$ (where $p_{FB}$ is failure pressure of bottom-to-shell joint).

Another significant remark related for safe margin ratio ($p_{FB}/p_{FR}$) is related to empty and full tanks. Small diameter empty tanks shows quite low $p_{FB}/p_{FR}$ ratio (according to Swenson [4] "joint failure ratio") 1,47-1,76, while full tanks has much higher and safe $p_{FB}/p_{FR}$ ratio 3,13-4,5 [4].

## 4. SOME ADDITIONAL ASPECTS OF DESIGN AND SELECTION OF FRANGIBLE ROOF TO SHELL JOINT

There are number of accident cases where appropriate selection of frangible roof-to-shell joint had provided successful emergency venting, and possible catastrophic event have been avoided. It is the basic function of frangible roof-to-shell joint to be a sacrificial joint on fixed roof storage tank structure and to provide emergency venting by "safe" rupture in event of significant increase of internal pressure. Process of failure (failure mechanics) could be quite different for different storage tanks. Some of them show failure of just of portion of roof-to-shell joint (10-20% of joint length, obviously enough to provide necessary emergency venting) while some shows complete rupture of joint and rocketing of complete roof away of tank. Damage level of rest of storage tank structure, particularly of tank shell (due to buckling) could be also different, as well as required repair costs if any is reasonable.

### 4.1. Short review of frangible roof-to-shell modeling and validation

According to available literature references the modeling of frangibility of roof-to-shell joint is a quite complex. There is a number of important issues that have to be considered as: 3D tank model, non-linear (inelastic) material model, non-linearity of foundation, buckling, uplift, fracture, combustion and explosion, venting, i.e. generally a dynamic large-displacement elastic-plastic tank response [3,4]. In addition validation of FEM model by experiment (even with scale model tanks) could be quite dangerous and requires specific equipment and outdoor requirements, i.e. laboratory simulation of explosion and further fracture of frangible roof-to-shell joint is not possible due to safety requirements. However, if there is an interest of oil companies, standardization organization and scientific institutions such outdoor experiments could be possible [4].

### 4.2. Frangibility of roof-to-shell joint and welding technology

It is a well known fact that welding technology, which is basically defined by welding process, filler material, heat input (concept $t_{8/5}$) can significantly influence mechanical properties of welded joint, especially of heat affected zone. The most important mechanical properties which define frangibility of weld are: strength (yield stress and tensile strength), plasticity (fracture elongation) and toughness. Those are the properties which may be quite different in comparison to parent (base) material. Therefore, more detailed assessment of frangibility of roof-to-shell joint should take into account weld mechanical properties and used welding technology. In addition, existence, type and size of weld imperfection, i.e. non-destructive examination has to be seriously taken into consideration. Finally, selection of welding technology which can provide brittle or ductile and tough weld, weaker or stronger weld, weld with acceptable quality level (level of imperfection) jointly with weld size have to be taken into consideration for developments of further frangibility criteria. Just as an idea, weld with required strength, but brittle enough to provide “fast” rupture of frangible roof-to-shell joint, with as less as possible degradation (plastic deformation due to buckling) of rest tank structure can be far economical choice (less damage – less repair if any is possible).

## 5. REMARKS

There are a number of examples where selection of frangible roof-to-shell joint has provided safe rupture of portion or complete tank roof away of shell. To select such sacrificial joint there is a number of requirements that have to be fulfilled. Especially for small size tanks those requirements could be non-compatible and further selection have to be carefully reconsidered. However, further developments of selection criteria for frangible roof-to-shell joint should consider welding technology. Making of strong enough for normal working condition but brittle enough weld for dynamic loads due to emergency conditions, as well as appropriate sizing could be reasonable. In addition, development of new specific weld quality level requirements could also be reasonable.

## 6. REFERENCES

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