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EVALUATION OF STRAIN AND EXHAUSTION LIMITS FOR VESSELS

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1. INTRODUCTION

Design rules for impulsively loaded vessels (ILVs) have been incorporated in Section VIII, Division 3 of the ASME Code since 2019, based upon earlier development of ASME Code Case 2564. These rules are particularly applicable to explosive containment vessels (ECVs) used to fully or partially contain the combustion products of explosives. Uses of these ECVs include containment of suspect luggage at airports, bomb disposal, containment of experiments on explosive devices, and destruction of chemical munitions (e.g., see [1,2]).

Practical design of ECVs almost invariably results in limited plasticity, which is permitted in Section VIII, Division 3 of the ASME Code in both the damage-based (local ductility exhaustion) limits in KD-232 as well as the more restrictive strain limits for impulsively loaded vessels in KD-240. Both sets of limits relate to local failure, which takes on particular importance for impulsively loaded vessels [3,4]. Satisfaction of both sets of rules is currently required for ILVs. This places a significant burden on the designer, particularly in view of the very low values of strain limits permitted in KD-240. However, the strain-exhaustion limits in KD-232 have been shown to be unconservative for ILVs [5]. One therefore wonders whether removing the overly restrictive KD-240 strain limits and appropriately modifying the unconservative KD-232 ductility exhaustion limits is a possible path forward.

An attempt at examining the procedure here for HSLA-100 used by LANL raises concerns similar to those expressed in [5] for other steel materials. Further, to the author's knowledge, the *basis and limitations* for the strain-exhaustion limits utilized in KD-232 are not fully documented. In addition, these strain-exhaustion limits relate to failure by material separation, well beyond the point of localization of strains. Because of the energy-based nature of the impulsive loading, some of this energy becomes preferentially absorbed as plastic energy in the small, localized volume of material, leaving little margin between the point of localization and the point of failure by material separation. Therefore, it does not seem reasonable to attempt to modify the KD-232 local strain-exhaustion procedure to replace the strain limits in KD-240.

The current KD-240 strain limits are summarized in Section 2. The localized, damage-based exhaustion limits are described in Section 3. Examples of the use of these limits are presented in Section 4, followed by Conclusions and Recommendations in Section 5. While the development of appropriate limits for ILVs is beyond the scope of this report, suggested guidelines for their development are presented in the Recommendations portion of Section 5.

2. LOCAL STRAIN LIMITS IN KD-240

The ILV strain limits are given in KD-240 in the 2021 version of Section VIII, Division 3 of the ASME Code. This Article is titled, "Additional Requirements for Impulsively Loaded Vessels", where full details are found. Focusing on *local* strain limits, these are presented in KD-240 (d):

"(d) For vessels subjected to either single or multiple impulsive loading events, the principal elastic-plastic strain components (ε_1, ε_2, ε_3) through the entire wall thickness shall be examined over strain cycles within a single-loading event, or strain cycles within successive loading events, respectively. The principal elastic-plastic strain components are used in determining the average through-thickness membrane strains and the linearized bending strains. The membrane and bending strains (inner and outer surface values) are then converted to equivalent plastic strains and compared to respective plastic strain limits, as follows:

(1) The average membrane equivalent plastic strain shall not exceed 0.2%.

(2) The linearized equivalent plastic strain shall not exceed 2% (1% at welds).

(3) The maximum peak equivalent plastic strain during the transient at any point in the vessel, as the result of the design basis impulsive loading, shall not exceed 5% (2.5% at welds).

The Designer shall consider the need to reduce these strain limits for areas of high biaxial or triaxial tension."

As noted above, these specifically apply only to ILVs, not to other vessels, such as statically pressurized vessels. Some of the challenges associated with these ILV strain limits include:

1. The strain limits are arbitrary. They do not reflect the variations in plastic strain capacity from material to material. As a result, the effective "factor of safety" of the vessel design varies, depending upon the material of construction.

2. The 0.2% limit on average membrane equivalent plastic strain is considered by the writer to be extremely low and design-limiting. This is particularly the case when the vessel is designed for multiple loading cycles, as rapid shakedown is not assured and strains can build up for repeated loading (See [6] for a discussion of pseudo-shakedown and associated large residual strain buildup for repeated loading).

3. The "linearized" equivalent plastic strain is difficult to interpret and evaluate; and the relevance is questionable, in the opinion of the writer.

4. Because of the transient nature of the response of an ILV to dynamic pulse loading, evaluation of the strain limits requires monitoring all strains in the vessel during the entire transient, which can be a significant effort on behalf of the analyst. This is especially true for vessels subjected to repeated loading.

Although the strain limits are considered "local", the membrane and bending limits do relate to a certain extent to overall structural collapse.

3. KD-232 LOCAL DUCTILE STRAIN EXHAUSTION LIMIT

This local-limit methodology utilizing strain exhaustion first appeared in Section VIII, Division 3, starting in 2007 following its introduction into Section VIII, Division 2. While the author is unaware of full documentation and validation of this particular methodology, examination of KD-232 reveals that it is based upon modern damage mechanics (ductile cavity formation, growth, and coalescence; recognition that equivalent plastic strain at failure is a function of stress triaxiality). It appears that the basic premise is that local failure is governed by the path-dependent accumulation of equivalent plastic strain, as modified by the Stress Triaxiality factor. When the accumulated equivalent plastic strain at any location in the structure (appropriately adjusted during the strain-accumulation process using the current local stress triaxiality factor) reaches a certain limit, local failure occurs. The methodology takes into consideration that the equivalent plastic strain at failure is determined by integration with time of the equivalent plastic strain rate, that it depends on the current stress triaxiality state and that it is path dependent. The methodology implemented in Section VIII, Division 3, bases the capacity of the material on three key material parameters. The parameters are related to slope of the strain hardening curve, to elongation, and to reduction-in-area.

An investigation of the KD-232 methodology and comparison with quasi-static data from notched round bar specimens was reported a decade ago [7]. Data were obtained on Chinese carbon steel and austenitic stainless steel. The authors found that ductile fracture strains were conservatively estimated by KD-232 for carbon steel but not for the stainless steel.

The strain levels at failure for round bar specimens are in the unstable softening region of the material, well beyond the range applicable to ILVs. Localization of strains occurs in ILVs in this region, and some of the impulsive energy imparted to the vessel by the blast becomes preferentially absorbed in a small volume of material as plastic energy, so little margin actually remains in the ILV once material instability is reached. ILVs are energy-controlled rather than load-controlled structures, such as conventional pressure vessels subjected to quasi-static loading.

The KD-232 methodology was also evaluated for application to ILVs in [5] utilizing experimental data on open cylindrical vessels constructed of API 5LX-42 mild steel and 304 stainless steel. It was found that the procedure of KD-232 was generally unconservative, i.e., strain limits were permitted by the code that, in most cases, significantly exceeded observed peak strains at vessel failure. It is concluded in [5] that the methodology is not appropriate, in its present form, for conservative ILV design, as would be expected because of the energy-controlled nature of the impulsively loaded cylinders. However, it is conjectured here that the tubes tested to failure in [5] apparently underwent primarily membrane action to failure, and it is unclear if these same conclusions would apply to structures with more bending action prior to failure.

Comparing the methodologies for limiting local strains in KD-240 and KD-232, the following observations are made:

1. KD-232 would be applicable for all individual points in the structure. It can therefore be related to the third rule in KD-240 regarding the 5% limit on maximum equivalent plastic strain anywhere in the structure. The first two requirements in KD-240 are somewhat more global as they relate, respectively, to membrane and bending strain limits over the cross section, rather than strain at a specific point. These requirements take on more of the role of a structural collapse mechanism rather than a local material failure. Therefore, they have no direct counterpart in KD-232.

2. The KD-240 5% equivalent plastic strain limit is an arbitrarily selected value. The KD-232 limit does attempt to utilize actual material properties, although in a non-conservative manner, as the most favorable of three key material parameters is selected rather than the least favorable.

3. Both approaches rely on the use of equivalent plastic strain. In the case of KD-240, there are specific limits that are evaluated. In the case of KD-232, the equivalent plastic strain "capacity" of a location in the structure depends on the stress triaxiality history.

Illustrations of the procedures and use of KD-232 are presented by way of two examples in the following section.

4. EXAMPLES ILLUSTRATING ISSUES WITH KD-232 FOR ILVs

4.1 Example 1: Single-Port Spherical Containment Vessel

A two-dimensional axisymmetric model of a representative spherical ECV was created using Abaqus, as shown in Figure 1a, by K. Fehlmann, LANL Group J-2 [8]. Ten elements were used through-thickness to accurately capture bending. The vessel was constructed of HSLA-100 steel, with top cover tied to the vessel port weldment, as shown in Figure 1b.

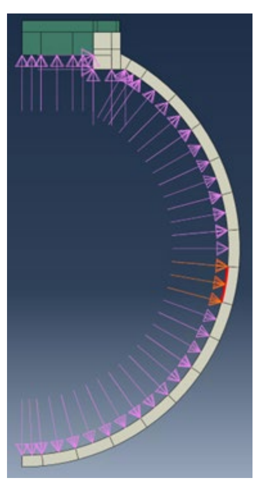


Figure 1a. Axisymmetric ECV Single-Port Model in Abaqus [8]

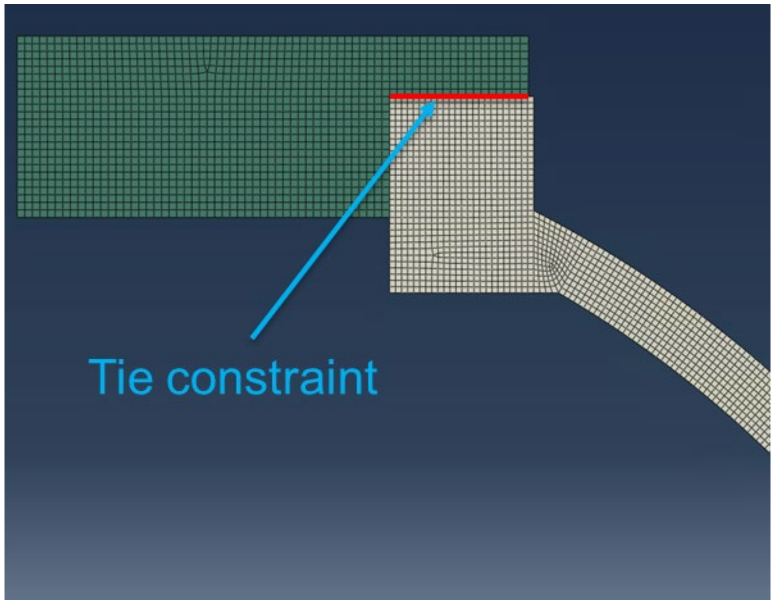


Figure 1b. Top Cover tied to Vessel Port Weldment [8]

A simplified, initially peaked, short duration triangular pressure pulse was utilized to simulate the impulsive pressure-time history of the contained explosive charge acting on the inner wall of the vessel. The loading was selected to induce limited plastic strains in the vessel. No initial or residual pressure was included. Results presented apply to the most highly stressed region at the bottom pole of the vessel, where the predominant plastic straining occurred. This location contains significant bending response in addition to membrane response.

The dynamic response phase calculated with the Abaqus model for a single impulsive loading is illustrated in Figure 2 for the case of linear isotropic hardening. Both stress- and strain-time histories for inner and outer elements at the bottom pole are shown in the figure. Both membrane and bending behavior can be observed. Results for linear kinematic hardening are similar.

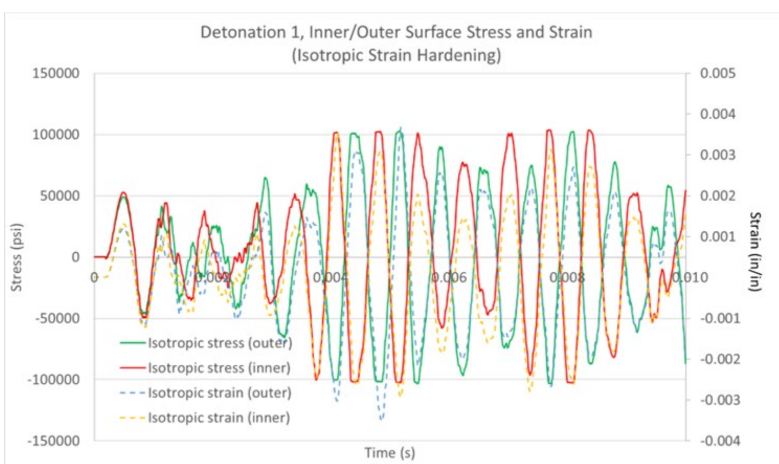


Figure 2. Transient Response Calculated with Abaqus Model at the Bottom Pole [8]

The vessel was then subjected to repeated, identical pressure pulses simulating repeated explosive detonations. Each detonation step was followed by a damping step to remove residual vessel motion. Equivalent accumulated plastic strain (Termed "PEEQ" in Abaqus) was determined at the outer element at the bottom pole at the conclusion of each loading cycle. Results for isotropic strain hardening are shown in Figure 3, where it is seen that the 5% equivalent-plastic-strain limit of KD-240 would restrict usage to (marginally) four HE tests. The additional equivalent plastic strain generated for each detonation cycle is seen to diminish, suggesting eventual shakedown to a steady value at large plastic strains. For an elastic-perfectly plastic model, accumulated plastic strain became unbounded due to the lack of strain hardening and the need to react the same amount of explosive input energy from one detonation to the next.

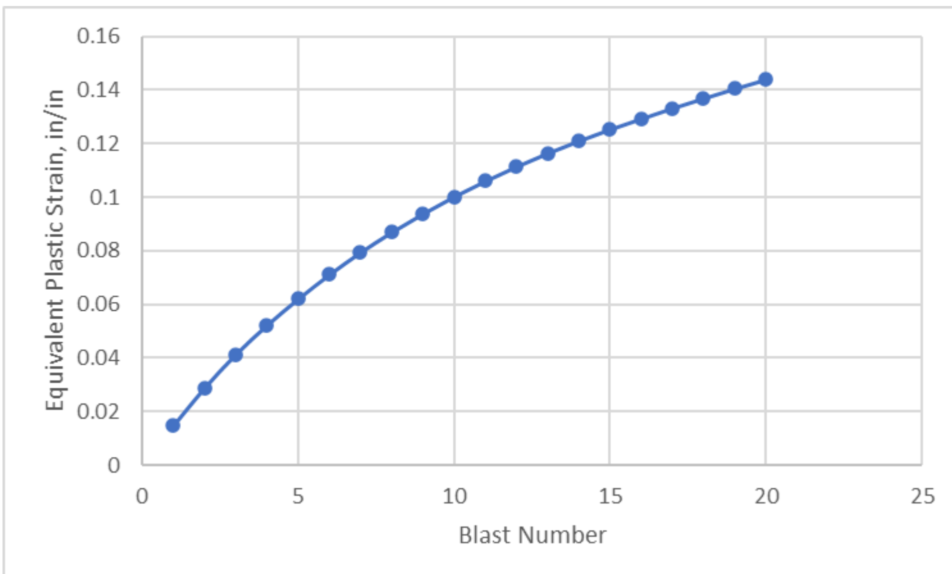
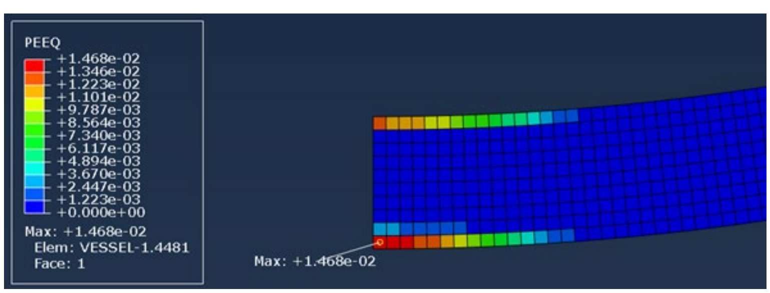
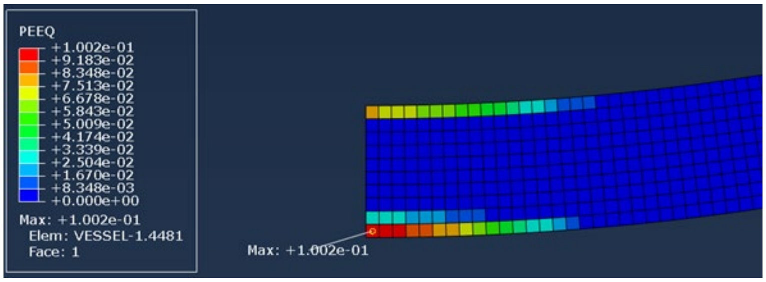


Figure 3. Equivalent Plastic Strain as a function of Detonation Number at Bottom Pole of ECV for Isotropic Hardening (After [8])

Change in equivalent plastic stain values in the vicinity of the bottom pole are shown for Detonations 1 and 10 in Figure 4 for isotropic hardening, where it is seen that the size of the yielded zone appears relatively static: Only the magnitude of the equivalent plastic strain changes significantly between Detonations 1 and 10.



Detonation 1



Detonation 10

Figure 4. Increments in Equivalent Plastic Strain in the Vicinity of the Bottom Pole [8]

Resulting equivalent plastic strain results for the elastic-plastic model with linear kinematic hardening are somewhat different, as shown in Figure 5. There appears to be a near-constant change in equivalent plastic strain from one detonation to another, implying continued ratcheting. However, equivalent plastic strain is a positive-definite quantity, so that both tensile and compressive straining would cause an increase in value, as illustrated in the following section. The continued growth in cumulative equivalent plastic strain corresponds to continued plastic cycling associated with plastic shakedown. As shown in Figure 5, the 5% equivalent-plastic-strain limit of KD-240 in the case of kinematic hardening would restrict vessel usage to three HE tests.

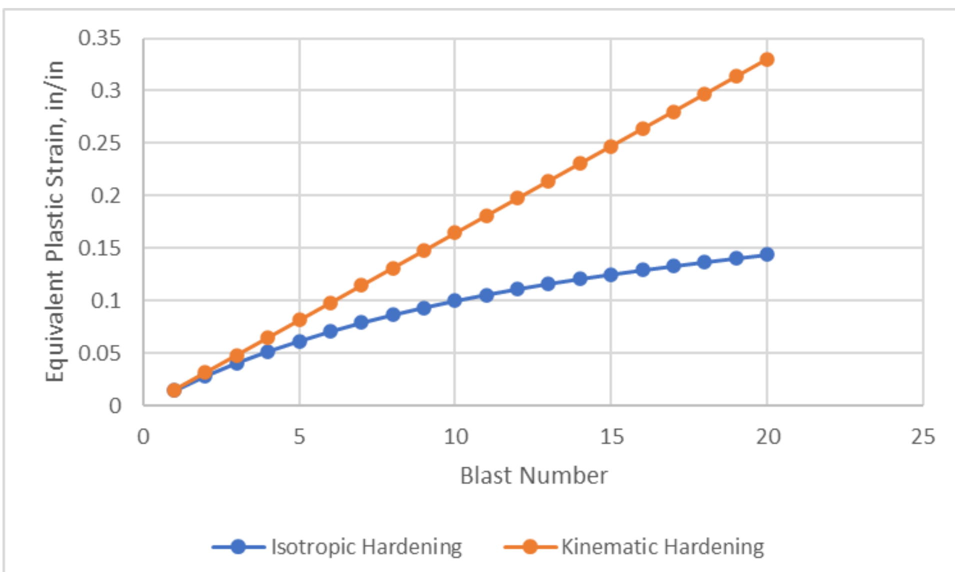


Figure 5. Comparison of Equivalent Plastic Strain Results (After [8])

Summarizing, for the ILV Strain limits rule 3 of KD-240: For maximum equivalent plastic strain less than 5%, the vessel can withstand (Based on Fig 5) 3 HE tests for the kinematic hardening model and (marginally) 4 HE tests for the isotropic hardening model.

Next, the procedure from KD-232 is Applied to HSLA-100 as follows to determine the corresponding equivalent plastic strain limit at the same location:

From Table KM-620 of ASME Code Section VIII-3 (2021) for ferritic steel,

$$m_2 = 0.60(1.00 - R)$$

where $R = \frac{S_y}{S_u}$

and S_y is the yield stress and S_u is the ultimate tensile stress of the material.

$$m_3 = 2\ln\left(1 + \frac{El}{100}\right)$$

$$m_4 = \ln\left(\frac{100}{100 - RA}\right), \text{ and}$$

$$m_5 = 2.2$$

where symbols are defined in Table 1.

Baseline properties for HSLA-100 are shown in Table 1:

Table 1
Baseline Properties for HSLA-100

Quantity	Symbol	Value
Yield Stress	S_y	100 ksi
Tensile Stress	S_u	115 ksi
Elongation	El	16%
Reduction of Area	RA	50%

Using these baseline properties, parameters become

$m_2 = 0.0783$
$m_3 = 0.297$
$m_4 = 0.693$
$m_5 = 2.2$

The limiting triaxial strain is

$$\varepsilon_{L,k} = \varepsilon_{Lu}\left[e^{\frac{-m_5}{1+m_2}\left(\frac{\sigma_{1,k}+\sigma_{2,k}+\sigma_{3,k}}{3\sigma_{e,k}}-\frac{1}{3}\right)}\right] \quad (1)$$

where σ_{ik} is the principal stress in the "i" direction at the point of interest for the k^{th} load increment, and

$$\sigma_{e,k} = \frac{1}{\sqrt{2}}\left(\left[\sigma_{1,k} - \sigma_{2,k}\right]^2 + \left[\sigma_{2,k} - \sigma_{3,k}\right]^2 + \left[\sigma_{3,k} - \sigma_{1,k}\right]^2\right)^{0.5}, \qquad (2)$$

the equivalent stress on the kth load increment. Here, ε_{Lu} is the maximum of m_2, m_3, and m_4.

For the element at the outer surface of the bottom pole, under a state of balanced biaxial stress,

$$\sigma_{1k} = \sigma_{2k} = \sigma$$
$$\sigma_{3k} = 0$$

Substituting into Equation (2), $\sigma_{ek} = \sigma$. Equation (1) then becomes

$$\varepsilon_{L,k} = 1.97\varepsilon_{Lu}$$

But ε_{Lu} is the maximum of m_2, m_3, and m_4, so

$$\varepsilon_{Lu} = 0.693$$

Therefore, $\varepsilon_{L,k} = 1.37$ in/in. This would correspond to 80 explosive tests (KD-232) in the case of kinematic hardening, as extrapolated from Figure 5. Recall that the 5% strain limit of KD-240 resulted in 3-4 explosive tests.

The corresponding circumferential strain at the bottom pole location would be

$$\varepsilon_\theta = \varepsilon_L / 2$$

Therefore, the resulting circumferential strain at the point of the strain exhaustion is 0.685 in/in. In any case, these are extremely large strains. A comparison of corresponding strain-exhaustion values under balanced biaxial stress for API5LX-42 Mild Steel from [5] is shown in Table 2.

Table 2
Strain Exhaustion Limits Comparison for Balanced Biaxial Stress

Parameter	HSLA-100 Steel	API 5LX-42 Mild Steel
S_y	100 ksi	45.6 ksi
S_u	115 ksi	80.4 ksi
El	16%	23%
RA	50%	60%
m_2	0.0783	0.260
m_3	0.297	0.414

m_4	**0.693**	**0.916**
m_5	**2.2**	**2.2**
ε_L	**1.37 in/in**	**0.512 in/in**
ε_θ	**0.685 in/in**	**0.256 in/in**

There is a "Local Criteria" load factor for elastic-plastic analysis listed in Table KD-230.4 ("Load Combinations and Load Factors for an Elastic-Plastic Analysis" as follows:

$1.28(P_D + P_S + D) + 100W_A$, where

P_D = Internal and External design pressure
P_S = Static head from liquid or bulk materials
D = Dead weight of the vessel, contents, and appurtenances, and
W_A = Assembly loads

This is a "Load Factor", and could be viewed as an effective "factor of safety". For the present, both P_S and D are ignored as they would be negligible for containment vessels in comparison to dynamic loads. Assembly loads, W_A, could be explicitly included in any dynamic analysis (e.g., bolt preload), but do not seem applicable to the example being evaluated here. So, the only local loading evaluated here would be P_D. The magnitude of the dynamic pressure would therefore be increased by the factor 1.28. It could be interpreted that the net effect is that the extremely large strain exhaustion limit would effectively be reduced to some degree due to this 'factor of safety', but the "allowable" strains will still be extremely large, at least for the HSLA-100 material.

4.2 Example 2: Cylindrical Open-Ended Vessel

Local-strain analysis of open-ended cylindrical shells containing explosive charges is fully described in [5], so only key results are presented here. A representative air-filled, cylinder, taken from [5,9], is shown in Figure 6. This is a mild steel seamless tube, 323 mm in diameter, 9.5 mm wall thickness with open ends. In this study [9], a set of 10 cylinders were subjected to increasing HE loads until failure by material separation was observed, resulting in an upper and lower bound in failure strain (Range in failure strain based on experiment with marginal containment and experiment exhibiting marginal failure). Finite element simulation of a strongly loaded cylinder from this set was performed [5] and variation in Triaxiality Factor (TF) during the damage accumulation phase, shown in Figure 7, reveals that the TF lies well within the range of uniaxial (1/3) and balanced biaxial (2/3) stress state. Results are presented in Table 3, along with results from a separate experimental program [5,10] utilizing water-filled, stainless-steel cylinders. KD-232 bounds for uniaxial and balanced biaxial stress were calculated for these extremes using procedures presented above, shown in the last column. It is seen that the experimental failure strain for the mild steel cylinders lies right at the lower bound of strain limit for KD-230. For the stainless-steel cylinders, cylinder failure actually occurs well below KD-230 values. Both cases illustrate the inadequacy of KD-230 for impulsively loaded vessels.

Table 3
Example Results for Cylindrical Shells from [5]

Source	Diameter, mm	Wall Thickness, mm	Material	Experimental Failure Strain, in/in	KD-230 Strain Bounds, in/in
Rushton [9]	323	9.5	API 5LX-42 Mild Steel	0.27-0.28	0.916 0.256
Proctor [10]	254	13.1	304 Stainless Steel	0.38-0.41	1.41 0.61

Figure 6. Representative Open-Ended Cylinder Results (Slightly below Failure Strain) From [5,9]

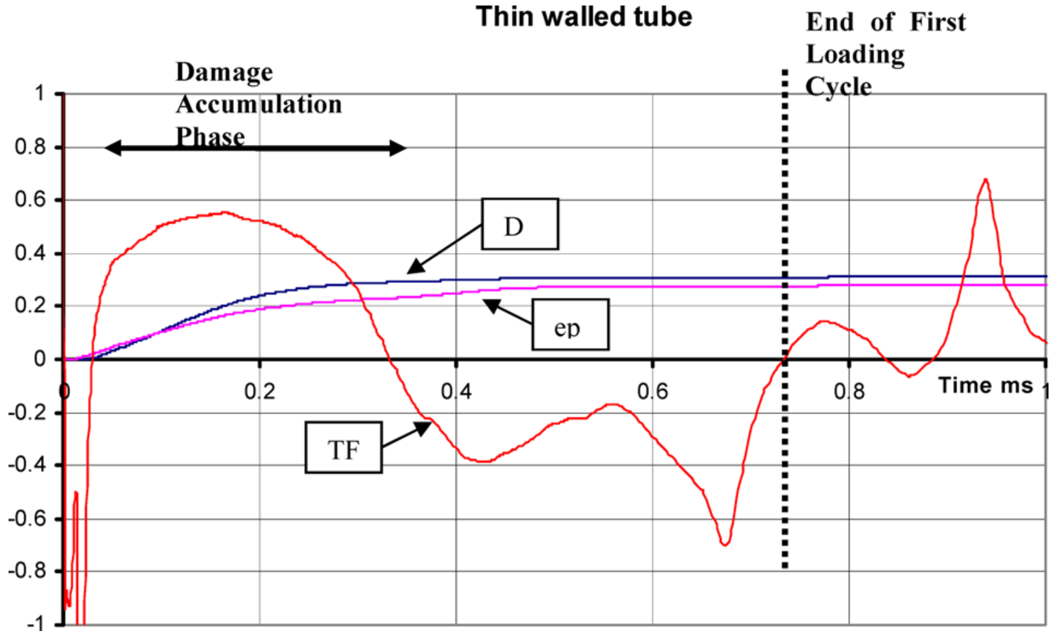


Figure 7. Variation in Triaxiality Factor for API 5LX-42 Cylinder [5]

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Shortcomings of the current ILV strain limits in KD-240 in the Code include:

1. The strain limits are arbitrary. They do not reflect the variations in plastic strain capacity from material to material. As a result, the effective "factor of safety" of the vessel design varies, depending upon the material of construction.

2. The 0.2% limit on average membrane equivalent plastic strain is considered by the writer to be extremely low and design-limiting. This is particularly the case when the vessel is designed for multiple loading cycles, as rapid shakedown is not assured and strains can build up for repeated loading (See [6] for a discussion of pseudo-shakedown and associated large residual strain buildup for repeated loading).

3. The "linearized" equivalent plastic strain is difficult to interpret and evaluate; and the relevance is questionable, in the opinion of the writer.

4. Because of the transient nature of the response of an ILV to dynamic pulse loading, evaluation of the strain limits requires monitoring all strains in the vessel during the entire transient, which can be a significant effort on behalf of the analyst. This is especially true for vessels subjected to repeated loading.

Shortcomings of the KD-232 local strain limits, as applied to ILVs, include

1. To the author's knowledge, the *basis and limitations* for the strain-exhaustion limits utilized in KD-232 are not fully documented.

2. An attempt at examining the procedure here for HSLA-100 used by LANL raises concerns (particularly, excessive permissible plastic strains) similar to those expressed in [5] for other steel materials.

3. The exhaustion limits are based on fracture by material separation, i.e., well beyond the point of instability and localization (e.g., necking). Because ILVs are impulsively loaded, they are energy-controlled rather than load-controlled, so all impulsive energy must be absorbed by the material in the localization region, which is small relative to the overall structure. Therefore, margin between the point of localization and material separation is actually small.

Therefore, for the above reasons, it does not seem reasonable to attempt to modify the local strain-exhaustion procedure to replace the strain limits in KD-240.

5.2 Recommendations

1. Strain or exhaustion limits should be based on actual material properties, rather than arbitrary limits.

2. Limits that are based on the softening region of the material should be avoided, as this is associated with localization of the material and energy absorption occurs over a small volume that is not particularly effective in capturing the impulsive energy.

3. A promising starting point is a maximum strain limit based upon some fraction of 'n' from a power-law fit to the stress-strain data. This point is associated with the initiation of material instability for bars, cylindrical and spherical shells [3,4].

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