

FAILURE BEHAVIOUR OF STEEL MATERIALS AND ACCEPTANCE CRITERIA FOR FREE-DROP DESIGN ASSESSMENT OF NUCLEAR WASTE CONTAINERS

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ABSTRACT

Steel waste containers shall be designed to maintain their structural integrity in all applicable loads. Maintaining such integrity during conceivable free-drop accidents is a design matter of great concern during on-site or in-facility lifting. The possible drop cases, such as crane failure during lifting operation, are important to public safety. A drop case can cause damage to the structural components, affect the shipping activities, and further cause leakage of radioactive material in the worst scenario. To evaluate the possible damage to a waste container for design purpose, in addition to testing, a sophisticated numerical analysis is commonly performed to account for geometrical and material nonlinearities, as well as structural stiffness degradation and strength deterioration during the free-drop impact. This paper is to present a method of analysis for the design of waste containers with 316L steel material using LS-DYNA model *MAT24, where the true stress-strain relationship is assigned and the output in terms of stress-strain relationship is calculated and assessed with the experimental result up to the onset of necking. The ASME acceptance criteria of effective plastic strain-based limits are applied with the LS-DYNA analysis for the design check of a steel waste container. It is identified that the true fracture strain rather than the code-accepted uniform necking strain should be taken as the criterion for element erosion in simulating fractural damage. Using LS-DYNA analysis with free-drop impact loading can achieve the design evaluation to meet code requirements.

INTRODUCTION

For the safe transport of radioactive materials in nuclear industry, the International Atomic Energy Agency (IAEA) has issued its specific safety guide (IAEA, 2014) that is applicable for the nuclear waste containers. Meanwhile, the Canadian Nuclear Safety Commission (CNSC), the United States Nuclear Regulatory Commission (NRC), and the United States Department of Transportation (DOT) have cooperated and issued a guide to facilitate the Canadian and American regulatory approvals (CNSC, 2009). These guides specify detailed requirements to demonstrate the ability of packages thoroughly and completely during transport to meet either Canadian or U.S. regulations. One of the important loading conditions considered for a package is the effects of free drop during transport. Detailed test requirements are provided by IAEA (2014) and CNSC (2009). The best way is qualifying the waste containers by the required benchmark testing such as the approach for the certification of CANDU Type B(U)-85 shipping container for the global transport of highly radioactive materials (Celovsky et al., 2003). For containing intermediate-level (IAEA, 1993) or low-level (Siskind, 1992) radioactive materials such as containing solid fuel channels from refurbishment, the waste containers may be qualified by testing or designed by analysis.

Unlike strength-based design, for free-drop impact condition local damage beyond material yield has to be considered, and the strain-based design acceptance criteria should be established. In meeting nuclear regulatory requirements, the revised portions in the latest ASME BPVC.III.3 (ASME, 2023a) have clarified that as an alternative to the stress-based criteria, strain-based acceptance criteria associated with energy-limited events such as container free drop can be applied to ensure the

structural integrity. In accordance with WB-3700 (ASME, 2023a), this paper is focused on the discussion of strain-based acceptance criteria detailed in ASME (ASME, 2023b) applied in the design check of steel waste containers by using the computer program LS-DYNA (2015) and illustrating how the plastic analysis is applied for the strain-based design.

DESIGN REQUIREMENTS BY DYNAMIC PLASTIC ANALYSIS

The most important requirements for a waste container during a potential drop case are to maintain its structural integrity and to permit its safe removal after the drop accident. Damage to a container shall not result in releases of radioactive materials that affect the safety of operation personnel and public. To meet safety requirement, the functional and performance requirements must be satisfied to prevent exposure of the public to the radioactive waste: the container body is expected to absorb the free drop impact energy without rupture by large undergoing plastic deformations; the lids are not expected to break away from the waste container body; and there is no loss of shielding to environment.

Material Failure Behavior

To maintain container integrity, the physical material behaviour should be evaluated for the plastic analysis. From Appendix EE-1120 of ASME (ASME, 2023b), stress-strain curves from quasi-static tests are usually post-processed as engineering stress-strain curves as shown in Figure 1. The produced true stress-strain relation curve is related to the instantaneous cross-sectional specimen area. Such stress-strain behaviour is similar to the stress-strain relationship in the explicit nonlinear dynamic analysis. Therefore, in the following test procedure of ASTM (2022), the variation of cross-sectional area A after necking should be recorded in order to determine the true stress-strain curve after necking. It is important to note that when the true stress-strain curve in Figure 1 is applied in the LS-DYNA analysis, the necking effect is automatically taken into account as the stress-strain relation after necking is used. The necking point is close to the onset of reducing the sectional area, at which the maximum load is reached. The stress-strain relation is further complicated by the development of radial and hoop stresses in the necking region. Thus, the uniform strain $\epsilon_{uniform}$ at necking initiating is used to define the design acceptance limit in the ASME code (ASME, 2023b). The average axial stress $\sigma = P/A$ is not the true equivalent uniaxial stress as the hoop and radial stresses are not zero. After necking point, the nominal stress is often corrected to get the true equivalent uniaxial stress using a Bridgman Correction factor (ASME, 2023b). In addition to uniform strain $\epsilon_{uniform}$, the true fracture strain $\epsilon_{fracture}$ is also used to determine the acceptance limits in Appendix FF (ASME, 2023b).

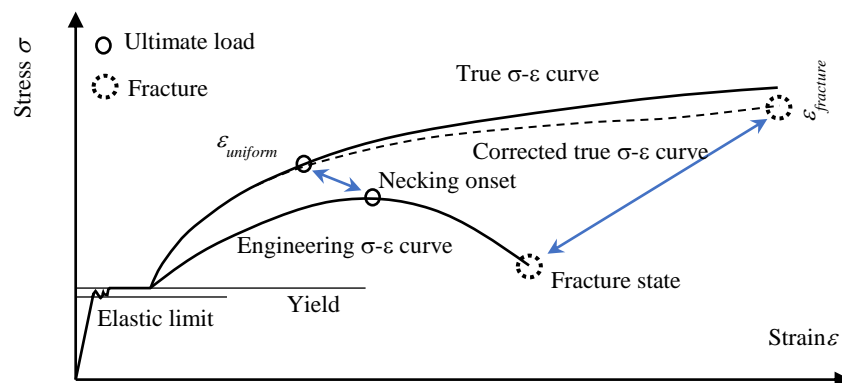


Figure 1. Stress-Strain Performance of Steel Material

Acceptable Materials for Waste Containers

In using the strain-based limits to design waste containers, the materials have to be tested to meet the requirement specified in Appendix FF (ASME, 2023b), where materials of SA-240 304L, 304, 316L,

and 316 are used for sheet plate only; materials SA-479 (excluding strain-hardened material), 304L, 304, 316L and 316 are used for bars and shapes. The reason might be that these materials have been tested for the application in energy-limited events such as free drop. For instance, from the U.S. DOE-supported test results, the material properties from the tests are summarized in Table 2 based on the existing research studies (Blandford et al., 2007). Two tests for the base metal plate with thickness of 0.5 in (12.7 mm), and other two tests for plate with thickness of 0.25 in (6.35 mm) are listed in Table 1. Under the condition of room temperature, the average uniform and fracture strains for the base metal with 12.7 mm thickness are 0.45 mm/mm and 1.783 mm/mm, respectively. The average yield strength is 243.05 MPa, but the minimum strength from Test #230468 is 199.27 MPa, which is close to the yield stress shown in Figure 2. For base metal with 6.35 mm thickness, the average uniform and fracture strains are 0.47 mm/mm and 2.101 mm/mm, respectively. The average yield strength is 273.39 MPa, which is greater than the yield strength for base metal with 12.7 mm thickness. For welds the results are only from two tests as shown in Table 2. For weld metal corresponding to base metal with 12.7 mm thickness, the uniform and fracture strains are 0.35 mm/mm and 1.308 mm/mm, respectively. These values are less than corresponding values from the test related to base metal with 6.35 mm thickness.

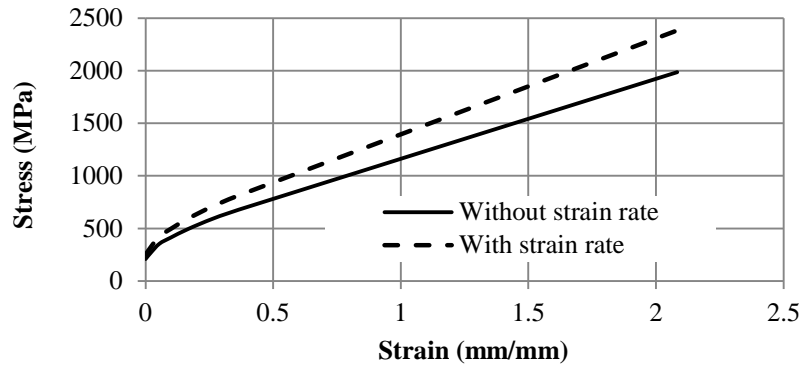


Figure 2. 316L Estimated ASME Code Stress-Strain at Room Temperature

Table 1: True Uniform and Fracture Strains of Base Metal at Room Temperature

Thickness (in/mm)	Test Number	Uniform Strain (mm/mm)	Fracture Strain (mm/mm)	Yield Strength (ksi)	Yield Strength (MPa)
0.5/12.7	230468	0.46	2.08	28.9	199.27
	67K0	0.44	1.486	41.6	286.83
	Average	0.45	1.783	35.25	243.05
0.25/6.35	48R8	0.46	2.112	37.7	259.94
	76H3	0.48	2.089	41.6	286.83
	Average	0.47	2.101	39.65	273.39

Table 2: True Uniform and Fracture Strains of Welds at Room Temperature

Thickness (in/mm)	Test Number	Uniform Strain (mm/mm)	Fracture Strain (mm/mm)	Yield Strength (ksi)	Yield Strength (MPa)
0.5/12.7	230468	0.35	1.308	56.3	388.19
0.25/6.35	48R	0.4	1.646	37.7	259.94

It is noted that the requirement for the materials applicable to waste containers is quite stringent. As the ASME code (ASME, 2023a and 2023b) is an international code, the tested data for the steel materials in the United States database might not be available for other countries. It is recommended, therefore, that if the true stress-strain curves associated with the corresponding uniform strain $\epsilon_{uniform}$ and fracture strain $\epsilon_{fracture}$ can be reasonably derived based on the properties of the selected materials, the material can be applied for the steel containers as long as the strain-based acceptance criteria are

met. The stress-strain curve of SA-240 306L is shown in Figure 2. In accordance with ASME code Section III Appendices EE and FF (ASME, 2023b), when the strain rate is over 5 mm/mm/s, the stress can be increased by 20% as also shown in Figure 2.

DROP ANALYSIS

A free-drop analysis is aimed at structural integrity assessment of a waste container for the indented drop scenarios. To meet the code acceptance criteria, the selected analysis tools should have certain features in modeling plastic behaviour and erosion (element removal) to capture the material fracture. The computer programs LS-DYNA (2015) or Abaqus (Abaqus/CAE, 2011) has the required features for the free-drop impact analysis. In this study, the analysis will be illustrated using the LS-DYNA finite element analysis computer software, which is a multi-purpose explicit and implicit finite element and multi-physics program used to analyse nonlinear response of structures. The LS-DYNA has a large element library to model different types of structures, and is capable of modelling various materials with nonlinear properties and failure models. The various types of contact-impact algorithms available in this software can effectively handle complex contact interaction between various surfaces subjected to impact loads. LS-DYNA has been extensively used to simulate various types of sophisticated impact problems in both nuclear and non-nuclear industries. These capabilities make LS-DYNA suitable for structural integrity assessment of the waste container during postulated drop events.

Theoretical Consideration

In Appendix EE (ASME, 2023b), the equivalent relation of true plastic stress and strain is expressed in terms of von Mises stress and strain. The corresponding equivalent plastic strain is formulated as:

$$\varepsilon_{eq}^p = \int_0^t \sqrt{\frac{2}{3} \dot{\varepsilon}_{ij}^p \dot{\varepsilon}_{ij}^p} dt \quad (1)$$

where the top dot indicates the strain rate. The equivalent plastic strain is an integral of the equivalent plastic strain rate over the time interval t , which corresponds to the true strain. The acceptance criteria in Appendix FF (ASME, 2023b) are defined based on the equivalent plastic strain Equation (1). It is noted that the equivalent plastic strain is a common variable calculated in nonlinear finite element software codes LS-DYNA, and details on the derivation can be found the theoretical manual (LS-DYNA, 2015) or Abaqus manual (Abaqus/CAE, 2011). The equivalent plastic or true strain is a cumulative, positive scalar value, and it is integrated in the entire deformation history. As the driving mechanism for plastic strain is the externally supplied kinetic energy impacts and drops, the equivalent plastic strain is intrinsically a better indication of the material condition than any instantaneous stress determination (ASME, 2023b), where the equivalent plastic strain cumulatively combines the strain history into a meaningful scalar value for comparative purposes. It is especially useful in reducing the voluminous strain output created by computer-based methods. The equivalent plastic strain does not indicate whether tension or compression has caused the strain, and the triaxiality factor should be used.

Modeling Consideration

For modeling purpose in finite element analysis, the nominal material properties required by ASME (ASME, 2023b) associated with true stress-strain curves are defined in LS-DYNA. In modelling the waste container, the nonlinear material parameters should be properly assigned to container main body and the connection bolts. For targets on which the waste container drops, the linear elastic model is used. For concrete targets, the strength of 35 MPa is normally used to determine the elastic modulus. A steel waste container may have a main body including the plates, stiffeners and lids, which can be modeled using shell elements. Connection bolts are modeled using beam elements. The contained inside waste is usually modeled by solid elements. In using LS-DYNA for the modeling, the following assumptions may be made. The target Concrete floor/base slab on which the container falls is assumed to behave linear elastic. This is conservative for assessing the container damage since

the kinetic energy is not dissipated by the plastic deformation in the concrete slab. This assumption is consistent with the unyielding requirement for container testing IAEA (2014). Particle waste inside the container may be simulated using 3D brick element with Mohr-Coulomb material model. This material model has been extensively used to model the behaviour of sand-type material, which is similar to the particle waste. The material density, shear modulus and Poisson's ratio are assigned to the waste material. The welded connections may not be explicitly modeled since the weld connection is not expected to fail before the base material. In such a case, the minimum strain-based criterion of base plates and welds dominates the failure.

The values of friction coefficients between various interacting surfaces are not known. The lower bound values of zero may be considered in the analysis in order to minimize the loss of energy due to friction, which will lead to more conservative response. Sensitivity analysis is recommended to determine reasonable modeling and parameters. In the free-drop analysis the mesh size may be based on the past experience and sensitivity analysis is needed. With using LS-DYNA *MAT024 model, the uncertainty is low for the key structural components of steel container. For linear elastic target, the greater Young's modulus may conservatively be used. Some other parameters are default in the LS-DYNA. For small waste particles similar to sand, the Mohr-Coulomb model is very good to simulate sand-type particles with very small stiffness. Such a model can properly capture the spatial mass distribution of the waste, and no friction is set to the contact between the waste and the container. A large-size solid waste is not allowed to free movement, and the solid brick or beam element type can be used. Accurate analysis models are required in using the ASME strain-based acceptance criteria (ASMEa and ASMEb, 2023). The element types with proper element aspect ratios should be checked. The contact points, friction, gaps, and boundary conditions are reasonably considered.

Element Erosion

In erosion technique to simulate the actual damage behavior, an element of the steel container is removed when it reaches at a predefined stress or strain or other parameters in LS-DYNA, and the element is thus eroded. Physically, a criterion for element erosion/removal should correspond to a parameter such as strain or stress at actual material rupture. In general, a design acceptance criterion should not be defined as an erosion indicator in the LS-DYNA analysis. For instance, consider the following extreme case when requiring the material behaves elastically from design functionality requirement. If elastic strain is set as a failure (erosion) limit in the LS-DYNA analysis, when the effective strain of an element reaches its elastic strain limit, this element is removed. The adjacent element will quickly reach the elastic strain limit and be removed. Finally, a hole caused by damage is created during the analysis. This analysis result can only show that the elastic design limit is reached and cannot reflect the actual fracture behavior beyond elasticity. Similarly, the code strain limits also cannot be used as the element erosion criteria as the actual fracture limit is not reached. On the other hand, for steel material the correct element erosion criteria should be related to the fracture state as shown in Figure 1.

ACCEPTANCE CRITERIA

From the assessment of waste container under drop loading, it is expected that the structural integrity shall be maintained, and no loss of shielding shall occur during each of the identified drop events. The following criteria are considered in assessing the structural integrity. The overall deformation of container waste body, lids shall permit the ability to restore their function after the stipulated drop event. This means plastic deformations should be limited to small local areas subjected to impact; and failure of bolts shall not cause a break-away of lids.

ASME Strain-Based Acceptance Criteria

To illustrate how to determine the ASME strain-based limits (ASME, 2023b), the properties of steel material SA-240 306L are taken into consideration. As per Appendix FF (ASME, 2023b), for material greater than $3t_n$ (where t_n is the adjacent nominal containment wall thickness) away from a gross or

local structural discontinuity, the strain limits are calculated in the following. The product of the equivalent plastic strain ε_{eq}^p and the associated Triaxiality Factor (TF) value at each evaluation location through the section, such as shell element through-thickness integration points, is calculated for each time interval. The average of these products through the wall section is given by:

$$[(TF)(\varepsilon\varepsilon_{eq}^p)]_{avg} \leq 0.67\varepsilon_{uniform} \quad (2)$$

For the SA-240 306L base metal with 6.35 mm thickness, the calculated limit is 0.315 for sheet plate. The maximum product of the equivalent plastic strain ε_{eq}^p and the associated TF value at any time at any container location is given by:

$$[(TF)(\varepsilon\varepsilon_{eq}^p)]_{max} \leq \varepsilon_{uniform} + 0.25(\varepsilon_{fracture} - \varepsilon_{uniform}) \quad (3)$$

For the SA-240 306L base metal with 6.35 mm thickness, the calculated limit is 0.878. For the waste container at locations within 3tn of a gross or local structural discontinuity, the acceptance strain limits are calculated in the following. The product of the equivalent plastic strain ε_{eq}^p and the associated triaxiality factor (TF) value at each evaluation location through the section, such as shell element through-thickness integration points, is calculated for each time interval. The average of these products through the section is given by:

$$[(TF)(\varepsilon\varepsilon_{eq}^p)]_{avg} \leq 0.85\varepsilon_{uniform} \quad (4)$$

For the SA-240 306L base metal with 6.35 mm thickness, the calculated limit is 0.4. The maximum product of the equivalent plastic strain ε_{eq}^p and the associated TF value at any time at any container location is the same as defined in Equation (3). If it is hard to distinguish the discontinuities, edges and corners for one type of material in the modeling, the determination can be done after analysis based on the location of strain response. Then, the proper acceptance strain limits are applied for the design check. In the design check using Equations (2) to (4), the Triaxiality Factor (TF) values can be determined using the table in Appendix EE (ASME, 2023b), where the stress state is known for the element having maximum equivalent plastic strain. Alternatively, the triaxiality time history can be obtained from the analysis, and the product of the equivalent plastic strain by the TF value at each time increment is calculated. The maximum value is compared with the value defined in Equation (2), (3) or (4). It is seen from Table EE-1150-1 in Appendix EE (ASME, 2023b) that the maximum TF value in bi-axial tension state is equal to 2. In this case, comparing to the three-dimensional equivalent plastic strain with the uniaxial tensile strain, the strain limit is reduced to half of the uniaxial strain limit. This means that the ASME strain-based limits take into account for the failure in complex stress state. It is noted for application that $3TF_{LS-DYNA} = TF_{ASME}$ as different TF definitions.

Design Acceptance Assessment

From the developed model and free drop analysis, the ideal result is that the waste container has large local plastic deformation, but the equivalent maximum plastic strain with accounting for the TF is less than the strain limits defined in Equations (2) to (4). On the other hand, if the calculated results cannot meet the ASME limits defined in Equations (2) to (4), the container integrity under drop conditions cannot be fully demonstrated for certain drop orientations, and technical measures must be applied to avoid the occurrence of such drop orientations during transport.

ILLUSTRATION OF LS-DYNA ANALYSIS AND ASME DESIGN CHECK

Analysis and Assessment of Simple Specimen

The purpose of the following analysis of a simple specimen is to illustrate dynamic response of a flat steel plate with 316L material with LS-DYNA material model *MAT24. The true stress-strain relationship for 316L stainless steel shown in Figure 2 is assigned to the *MAT24 model and the output in terms of engineering stress-strain relationship is calculated and compared with the

experimental one up to the onset of necking. In addition, the necking and failure response behaviour is investigated and the ASME design check is presented. For this analysis, a shell plate with length of 145 mm, width of 20 mm and thickness of 1.5 mm is used, and the model with mesh grid is shown in Figure 3, where the left end is constrained in all DOFs except for in y-direction; this allows the large deformation in the plate plan. On the right end, only the center node is constrained in y direction to maintain the geometric stability. A displacement motion is uniformly applied on each node at the right end.

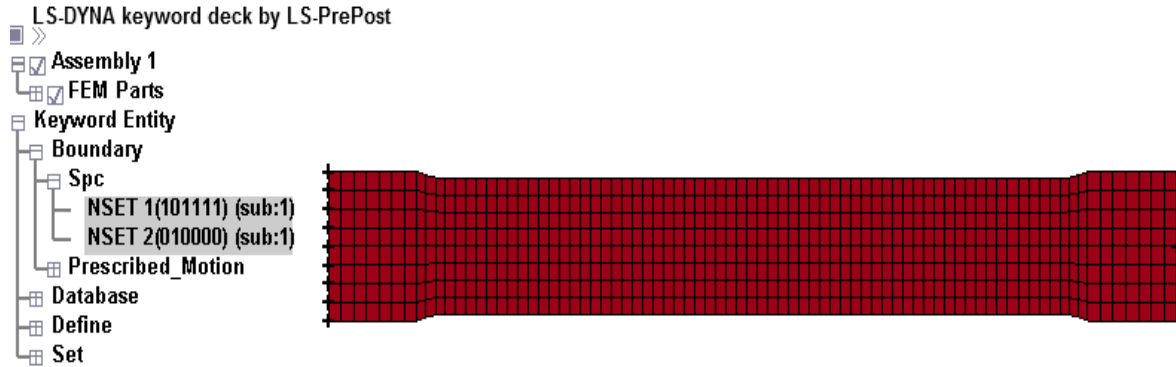


Figure 3. LS-DYNA Model for a Steel Plate

For the analysis, the true stress-strain curve from the test results presented in Figure 2 is used. This curve was estimated at room temperature for the true ASME Code minimum stress-strain curve of 316L material developed from the typical test data. The true fracture strain is about 2.1 mm/mm corresponding to true fracture stress of 199.9 MPa (29 ksi). The Young's modulus of 200 GPa, yield stress of 170 MPa, and Poisson's ratio of 0.29, are used for the analysis. For a comparison between simulated and tested stress-strain curves, from the LS-DYNA analysis, the force at middle section of plate and displacement at its end are obtained. The engineering stress is then calculated by dividing the section force by the initial area of the section; the engineering strain is calculated by dividing the elongation by its initial length. It is found that the simulated engineering stress-strain relationship is in well agreement with the one reported by experimental measurements up to onset of necking. From the LS-DYNA analysis, the plate maximum displacements versus time are shown in Figure 4. The calculated engineering strains are 0.331 mm/mm, 0.563 mm/mm, 0.64 mm/mm, 0.651 mm/mm, and 0.662 mm/mm at the time moments, where the original length 145 mm is used.

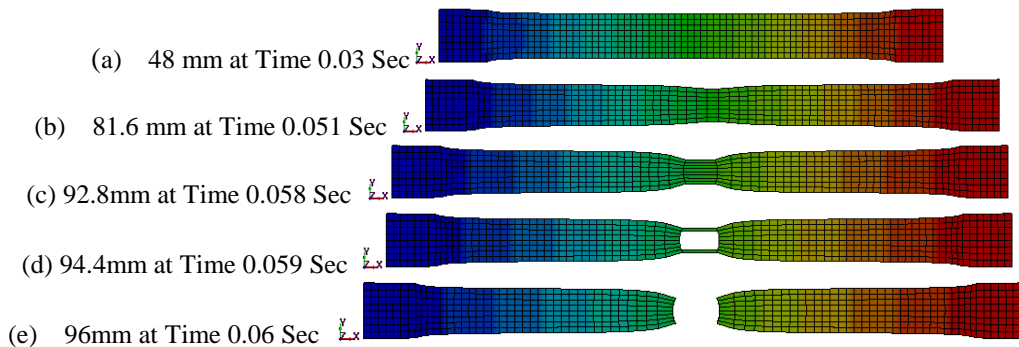


Figure 4. Plate Maximum Axial Deformation

For evolution of equivalent plastic strain, from the LS-DYNA analysis, the evolution of Effective Plastic Strain (EPS) is presented in Figure 5. It is seen that the effective plastic strain of 0.317 mm/mm is less than the engineering strain of 0.331 mm/mm at time 0.03 sec. However, the effective plastic strains at and after 0.051 sec are far greater than the corresponding engineering strains.

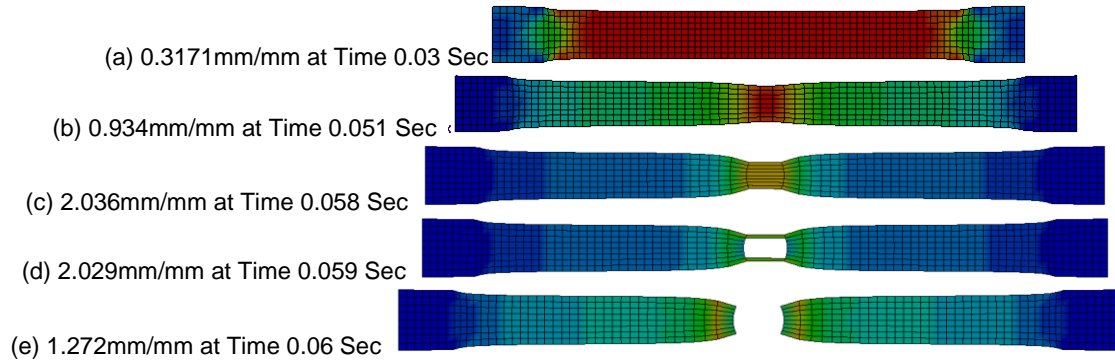


Figure 5. Evolution of Maximum Equivalent Plastic Strain

For ASME design check, it is seen from Figure 5 (a) and (b) that the maximum EPS occurs at the middle of the steel plate. Thus, to use Appendix FF of ASME code (ASMEb, 2023) to check the design acceptance, a critical element at the center place is selected to output the EPS and TF time histories. The EPS is shown as the dashed curve in Figure 6, where the red curve is the product of ASME TF and EPS. For the steel 306L, the design acceptance strain for average cross section is 0.315 mm/mm as shown in solid black line, and the max acceptance strain is 0.878 mm/mm as the purple line in Figure 6. It is seen that the plate at ASME acceptance strain of 0.315 mm/mm behaves in uniform strain manner as shown in Figure 5(a), and at acceptance strain of 0.878 mm/mm the ASME TF is slightly greater than 1. The structural integrity of the steel plate is maintained at these acceptance criteria.

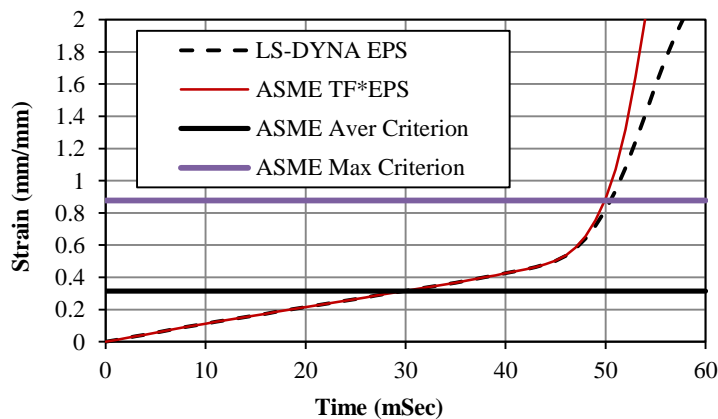


Figure 6. ASME Strain-Based Design Check

Cylindrical Waste Container

A model of a steel waste container with the concrete target under inclined drop case is developed as shown in Figure 7(a). The drop analysis is performed based on the initial velocity determined from a drop height. The possible drop cases, such as a crane failure during lifting operations are identified. Explicit dynamic analyses are carried out for critical container orientations such as corner or side impact. This analysis illustrates the scenario of 45°-angle-inclined impact. The numerical analysis accounts for the geometrical and material nonlinearities and structural rupture during each drop case. The purpose of the drop analysis is to ensure waste container integrity, and to quantitatively estimate the damage behavior based on the acceptance criteria.

The applied material SA 240-316L has the following properties: modulus of elasticity of 200GPa, Poisson's ratio of 0.29, density of 7750 kg/m³, true uniform strain of 0.46 mm/mm, and true

fracture strain of 2.08 mm/mm as shown in Figure 2. The necking and fracture strains for 316L weld metal at room temperature are 35% and 130.8%, which are respectively less than the corresponding strains of 46% and 208% for the 346L base metal at room temperature. Thus, the smaller necking and fracture strains from 316L weld metal can be used as strain acceptance criteria for the drop analysis. In an inclined drop condition, the bottom edge of the waste container impacts on the flat concrete target with initial velocity calculated by the drop height of about 4 m. The concrete floor is assumed rigid so that it is conservative for assessing the damage of the steel container.

In the drop impact analysis, the element erosion criterion can be set to the ASME allowable strain 0.23 mm/mm ($=0.67 \times 0.35$ mm/mm), or the true fracture strain of 1.308 mm/mm. Since ASME design acceptance criterion is based on the allowable plastic strain, the true allowable strain is used for element erosion. From the analysis, the effective plastic strain of a critical element at time 28 ms is shown in Figure 7(b). It is seen that the calculated maximum effective plastic strain is 11.5% corresponding to the ASME allowable strain with considering the calculated TF value of about 2.0 mm/mm. This maximum strain occurred at around the contact area between the steel container and target concrete slab as well as around the bottom steel plate. The maximum plastic strain value has reached and gone beyond the allowable strain defined in the ASME code for the 316L stainless steel materials. On this basis, the tank shell of waste container will not meet ASME plastic strain-based acceptance criteria in such a drop scenario.

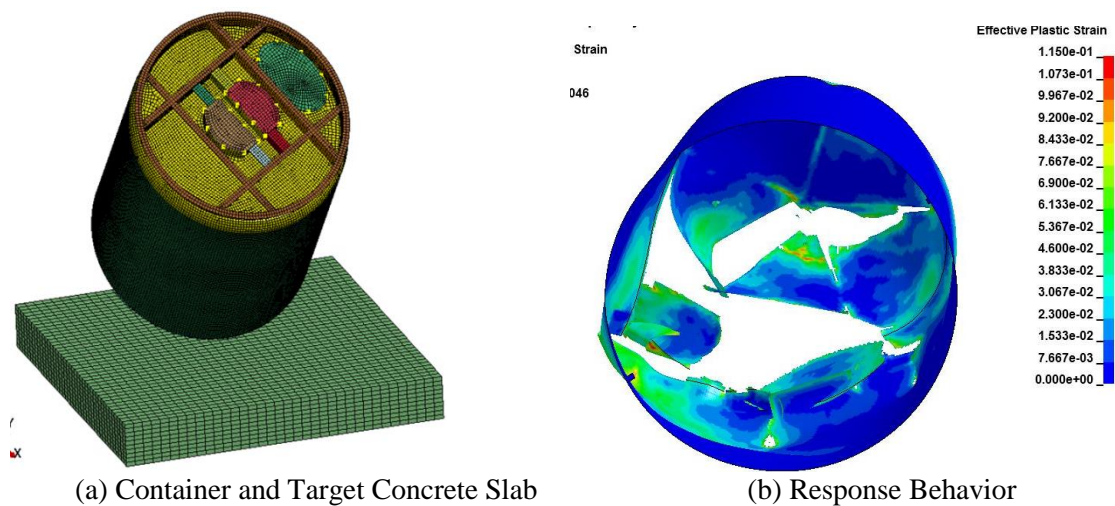


Figure 7. Modelling and analysis result of a waste steel Container

Discussion on Element Erosion Criterion for Design Assessment

It is noted that the simulated fractural failure in Figure 7(b) is not true as the uniform necking strain is used as a criterion for deleting element. The structural failure and the corresponding design acceptance criteria are based on the stress-strain performance of the structural materials. The stress-strain relationship shown in Figure 1 is illustrated for middle-steel material. The serviceability design is based on the elastic limit and the strength design is based on the yield strength and ultimate tensile strength following the engineering σ - ϵ curve to meet code requirements associated material resistance factors. The objective of design is to prevent the failure before reaching the ultimate design-basis loads applied on the structure.

On the other hand, for impact or impulsive loads such as container free-drop, local large deformation is expected, and the plastic strain is used as design acceptance criterion. The true σ - ϵ curve in in Figure 1 is followed and the objective of design is to prevent the failure of structural fracture. In the strain-based elastic-plastic dynamic analysis, the steel material experiences elastic limit, yield state, necking, and rapture. The plastic-strain based design is focused on the necking start

point close to the onset of reducing the sectional area, at which the maximum load is reached, but the structure is not fractured. It is obvious that only the true fracture strain rather than the elastic design limit, yield state or necking start strain can be used as a criterion to delete the element once the corresponding strain is reached.

CONCLUSIONS AND RECOMMENDATIONS

This paper presents the analysis method for design of steel waste containers, and the ASME required strain-based limits, and the application of LS-DYNA software. It is concluded that the true stress-strain curves from testing can be used in the free-drop impact analysis; comparing with testing results, the true stress-strain relation and the behavior of necking up to fracture can be well simulated using LS-DYNA material model *MAT24 for steel plates. From the evaluation of stress-strain performance of steel plates, the actual fracture strains rather than the design strain limits should be used in the simulation in determining element erosion to capture the actual fracture failure phenomenon. The ASME design check should be performed based on the distribution of critical EPS with TF after the plastic analysis. Using LS-DYNA dynamic plastic impact analysis can achieve the assessment to meet ASME strain-based design requirements. However, a code method in nuclear industry for strain-based design is not matured yet, and the method in non-mandatory Appendix EE and FF of ASME code (ASMEb, 2023) is still in developing. In applying the explicit dynamic analysis of waste container drop analysis for design assessment, it is recommended that the computer code (say LS-DYNA) should provide outputs for the averaged through-section EPS with TF to facilitate the design check to meet code requirements. The design code developers should specify acceptance criteria that correspond to the computer output feature and capability to facilitate application for engineers/analysts.

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