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Failure Criteria in Crashworthiness Analysis of Ship Collision and Grounding Using FEA: Milestone and Development

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Abstract
This study presents reviews of the failure criteria to capture the resulting response due to the catastrophe of ship collision and grounding using the finite element. Researchers have introduced several failure criteria, for instance, the DNV RP-C204 criterion, Germanischer Lloyd criterion, Peschmann, Rice-Tracey and Cockcroft-Latham (RTCL), Bressan-Williams-Hill (BWH) instability criterion, and Liu criterion. As in the mathematical formula, each criterion has a difference. The choice of failure criteria will depend on the simulation's specific requirements and the analysis's goals. Liu's criterion can be used to evaluate the failure of materials in ship collision simulations, for example, when large element sizes (i.e., 20 mm) are considered in the simulation.

1 Introduction

Ship collision modeling involves simulating and analyzing the potential outcomes of a collision between two or more ships. This can include factors such as the ships' speeds and trajectories, the sea conditions, and the actions taken by the ship's crews [1-3]. The goal of collision modeling is to identify potential hazards and develop strategies to prevent collisions from occurring. This can include developing new navigation systems, implementing new safety procedures, and training crew members to react quickly and effectively in the event of a collision [4].

The mesh size used in the finite element analysis method (FEA) significantly impacts the results obtained, with different mesh sizes yielding different outcomes compared to experimental results. Conducting nonlinear finite element simulations of ship collisions requires several essential input parameters, including the definition of the material, such as the actual characteristic stress-proper strain behavior and representative failure criteria, to estimate the critical failure strain of the finite elements. Other critical factors that influence finite element predictions include the type of finite elements used for collision simulations, the boundary conditions, the definition of the contact, and the associated static friction. Studies have shown that an accurate definition of material nonlinearities and finite element size is essential for a practical nonlinear finite element ship-to-ship collision simulation [5].

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Nevertheless, other input parameters, such as approximations of external dynamic loadings and modeling of structural details, also affect finite element predictions. In a study by Jones (2013) [6], various factors that impact the credibility of finite element predictions for structures subjected to significant dynamic loadings were discussed. Although Jones' discussion was for a general dynamic design application, and the evaluated dynamic loadings may be more substantial than those anticipated in a real ship collision scenario, the conclusions and ideas presented in the study are relevant to ship collision analyses.

The problem of direct experimentation requiring much money to analyze the response in a ship collision scenario can be overcome using finite element analysis. As a result, ship structural crashworthiness analysis and estimation of safety limits accounting for ship collisions can be obtained, which usually requires much money for direct experimentation. Finite element analysis (FEA) is a numerical method used to analyze the structural behavior of ship hulls during a collision. The FEA model simulates the ship's response to impact loads, such as those encountered during a collision, by dividing the ship's structure into smaller, manageable components called finite elements. These elements are then analyzed using mathematical equations to determine their behavior under different loads [7-12]. The analysis results can be used to evaluate the strength and integrity of the ship's structure and identify potential areas of weakness that may need to be reinforced. The FEA can be used to simulate different types of collisions, such as head-on, quartering, and oblique collisions, and can be used to evaluate the safety and performance of both new and existing ships [13-14]. In recent years, several failure criteria can be used in numerical finite element analysis (FEA) to evaluate the structural behavior of a ship during a collision or grounding event. Some standard failure criteria include the DNV RP-C204 criterion [15], Germanischer Lloyd criterion [16], Peschmann criterion [17], RTCL criterion [18], BWH: Bressan-Williams-Hill instability criterion [19], and Liu criterion [20].

It should be noted that the choice of failure criterion depends on the type of material, loading condition, and the level of accuracy required for the analysis. Also, it is essential to consider that these criteria are based on the assumptions and simplifications of the real-world scenario. The results should be compared with experimental data and real-world observations.

This work presents a comprehensive review of the main failure criteria used in finite element modeling of the structural behavior of ships in a collision scenario. The primary focus of this study is to compare and contrast the different failure criteria used in the field based on their basic calculations, methodology, failure criteria, maximum strain, and mesh size dependency. This research aims to critically assess the various methods, highlighting their strengths and weaknesses to facilitate more informed decision-making when selecting the appropriate failure criteria for a given application. By evaluating the various methods, this study hopes to contribute to the advancement of finite element modeling techniques for ship collision scenarios. The findings of this research are presented in a conclusive discussion, followed by future research directions that could expand on the work presented in this paper.

2 Failure Criteria

The science of material failure theory predicts the conditions that lead to the failure of solid material due to external load. Ship collision modeling employs several failure criteria related to crack initiation models, including those based on accumulated strain, triaxial stress state dependence, and forming limit diagrams. Among these, the maximum plastic strain criteria are the most used in ship collision modeling. This is due to its simplicity, as it relies on only one variable (equivalent plastic strain) and can be calibrated easily using a uniaxial tensile test. The maximum plastic strain criteria are also based on material properties, such as uniform and necking strain. For the implementation of failure criteria, material model 123 of ANSYS LS-DYNA [21] can be used. Material 123 is a modified piecewise linear plasticity model that uses the stress versus strain curve and allows fractures based on plastic thinning. The material definition requires the input of pre-calculated critical strain values.

2.1 DNV RP-C204 criterion

A simple fracture criterion based on the relationship described in Equation 1 with the following coefficients is given in DNVRP-C204 [15].

$$\varepsilon_f = 0.02 + 0.65\frac{t_e}{l_e}, \quad \frac{l_e}{t_e} \geq 5 \tag{1}$$

However, whether this is an equivalent or principal strain criterion is not specified in Equation 1.

2.2 Germanischer Lloyd criterion

The through-thickness strain criterion, based on the experimental measurement of the through-thickness strain of damaged plates in actual ship structures subjected to ship collision and grounding accidents, was initially proposed by Germanischer Lloyd AG [16]. The expression for the maximum equivalent plastic strain obtained by

$$\varepsilon_f(l_e) = \varepsilon_g + \varepsilon_e\left(\frac{t_e}{l_e}\right) \tag{2}$$

Equation 2 is also expressed as a function of the element size by employing two components, where ε_g the constant through-thickness strain and ε_e is the necking strain. These two components were obtained experimentally so, resulting in $\varepsilon_g = 0.056$ and $\varepsilon_e = 0.54$ for shipbuilding steel (considering plate structures), $\varepsilon_g = 0.079$ and $\varepsilon_e = 0.76$ if beams or trusses. t_e and l_e are the thickness and length of the element, respectively. Furthermore, the ratio $l_e/t_e \geq 5$.

2.3 Theoretical background of the criterion based on Peschmann

The following expression can be used to estimate the equivalent plastic strain at failure, which is the basis for the Peschmann criterion [17]

$$\varepsilon_f(l_e) = \varepsilon_g + \alpha \cdot \frac{t_e}{l_e} \tag{3}$$

where ε_g is the constant strain, $\alpha = \varepsilon_m \cdot (x_e/t)$ is a factor that depends on the necking strain and length of the neck, t_e is the thickness of the plate, and l_e is the length of the individual elements. Experimentally measured parameters for this expression in the hull tanker collision test resulted in $\varepsilon_g = 0.1$ and $\alpha = 0.8$ for plate thicknesses ≤ 12 mm and $\varepsilon_g = 0.08$ and $\alpha = 0.65$ for plate thicknesses between 12.5 and 20 mm.

2.4 Theoretical background of the criterion based on RTCL

The RTCL criterion, developed by Törnqvist in 2003 [18], combines two well-known failure models, the Rice-Tracey [22] and the Cockcroft-Latham criteria [23], with the intent of covering an extensive range of triaxialities. The Rice-Tracey criterion predicts well failure by void growth at high triaxialities, while the Cockcroft-Latham criterion gives good predictions for ductile shear fracture at low triaxialities. The RTCL criterion is given by

$$D_i = \frac{1}{\varepsilon_0}\int f\left(\frac{\sigma_H}{\sigma_{eq}}\right)_{RTCL} d\varepsilon \tag{4}$$

where

$$f\left(\frac{\sigma_H}{\sigma_{eq}}\right)_{RTCL} = \begin{cases} 0 & for \quad \frac{\sigma_H}{\sigma_{eq}} \le -\frac{1}{3} \\ 2\dfrac{1+\frac{\sigma_H}{\sigma_{eq}}\sqrt{12-27\left(\frac{\sigma_H}{\sigma_{eq}}\right)^2}}{3\frac{\sigma_H}{\sigma_{eq}}+\sqrt{12-27\left(\frac{\sigma_H}{\sigma_{eq}}\right)^2}} & for \quad -\frac{1}{3} < \frac{\sigma_H}{\sigma_{eq}} < \frac{1}{3} \\ \frac{1}{1.65} exp\left(\frac{3\sigma_H}{2\sigma_{eq}}\right) & for \quad \frac{\sigma_H}{\sigma_{eq}} \ge \frac{1}{3} \end{cases} \tag{5}$$

Where D_i is the integral function of damage, ε_0 is the uniaxial damage strain. The ratio $\frac{\sigma_H}{\sigma_{eq}}$ is called triaxiality, where the hydrostatic stress and the equivalent stress are defined as

$$\sigma_H = \frac{\sigma_{ii}}{3} \tag{6}$$

and

$$\sigma_{eq} = \left(\frac{3}{2}s_{ij}s_{ij}\right)^{\frac{1}{2}} \tag{7}$$

The deviatoric stress tensor is defined as $s_{ij} = \sigma_{ij} - \delta_{ij}\sigma_H$ where δ_{ij} is Kronecker's multiplier.

Due to its strong influence, Törnqvist [18] formulated the critical value for the integral function of damage D dependent on the element length in the loading direction l_e as.

$$D_{cr} = n + (\varepsilon_n - n)\frac{t_e}{l_e} \tag{8}$$

where D_{cr} is the critical value of the integral function of damage. The power law determines the uniform necking strain ($\sigma = k\varepsilon^n$) exponent n. Considering a uniaxial tensile test, ε_n is the failure strain obtained from $\frac{t_e}{l_e} = 1$, where t_e is the element thickness, and l_e is the element length. For shipbuilding steel, $n = 0.205$ and $\varepsilon_n = 0.67$.

2.5 BWH: Bressan-Williams-Hill instability criterion

The onset of local instability (incipient necking) can be estimated by combining Hill's local necking analysis [24] with the Bressan-Williams shear stress criterion [25] as proposed by Alsos et al. [19] in the BWH instability criterion for $-1 < \beta \le 1$. The following formula expresses the Bressan-Williams-Hill instability criterion:

$$\sigma_1 = \begin{cases} \frac{2K}{\sqrt{3}} \dfrac{1+\frac{1}{2}\beta}{\sqrt{\beta^2+\beta+1}} \left(\frac{2}{\sqrt{3}}\frac{\hat{\varepsilon}_1}{1+\beta}\sqrt{\beta^2+\beta+1}\right)^n & for \quad -1 < \beta \le 0 \\ \frac{2K}{\sqrt{3}} \dfrac{\left(\frac{2}{\sqrt{3}}\hat{\varepsilon}_1\right)^n}{\sqrt{1-\left(\frac{\beta}{2+\beta}\right)^2}} & for \quad 0 < \beta \le 1 \end{cases} \tag{9}$$

A geometric mesh scaling factor is incorporated as a selectable option in the formula where the critical strain $\hat{\varepsilon}_1$ can be assumed to be equal to the power law coefficient n following Hill's criterion [22], in which

$\hat{\varepsilon}_1$ in Equation 9 scales with the factor $\frac{1}{2}\left(\frac{t_e}{l_e}+1\right)$ as a remedy for coarse meshes that do not capture the actual local strain concentrations.

2.6 Liu criterion

Liu et al. [20] introduced a new failure criterion for ship collision assessment. A new expression was provided to predict the effective critical failure strain ε_f of coarse meshed by the new criterion.

$$\varepsilon_f = 0.50 - 0.01\frac{l_e}{t_e} \tag{10}$$

Equation 10 shows that the failure strain decreases linearly with the mesh size, which indicates that the necking strain is 0.50 and that the l_e is the length of the finite elements and t_e is the plate thickness.

3 Overall Discussion

Review the main failure criteria used in finite element modeling of the structural behavior of ships in a collision scenario that is being conducted, Table 1. The failure criteria proposed by the researcher have differences in the basic failure strain calculations. For example, suppose the ship collision simulation uses an element length of 10 mm and a plate thickness of 2 mm. In that case, the DNV RP-C204 criterion, Germanischer Lloyd, Peschmann, and Liu will give failure strain values of 0.15, 0.164, 0.26, and 0.45, respectively. These results follow the study conducted in the literature [20, 26-28]. As seen in Figure 1, the Liu criterion will give a failure strain of around 0.45 if the ratio $\frac{l_e}{t_e} = 5$.

Figure 2 shows the results of generated energy during the quasi-static indentation experiments of stiffened plates and double-hull structures [20]. The tests by Liu et al. [20] used a rigid cone indenter with a hemispherical nose to punch the small-scale specimens. The reported results include force-displacement responses and deformation modes. As can be seen, the Liu criterion showed a more reasonable prediction regarding energy-displacement capacity when a smooth and large indenter is used.

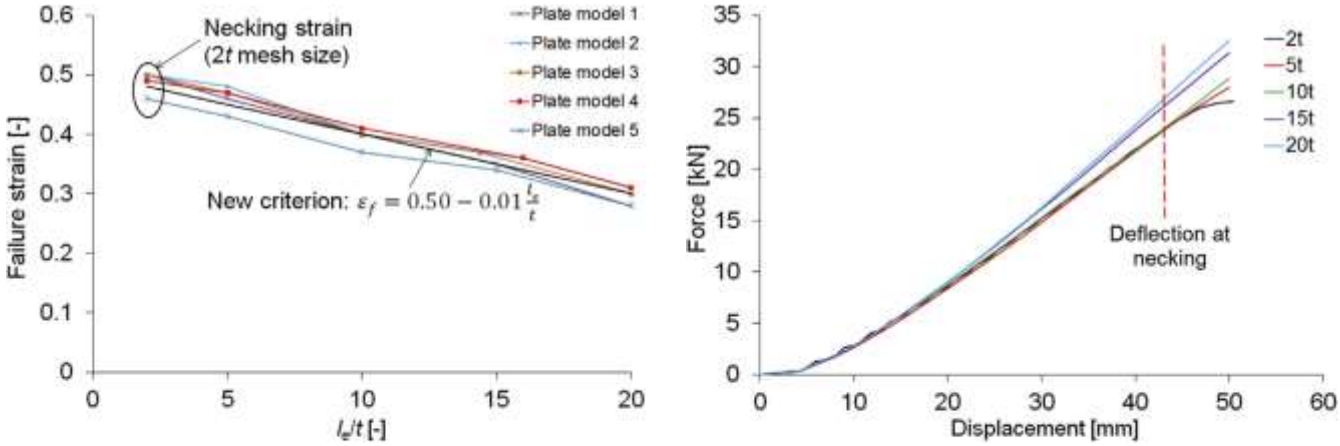
Table 1. Comparison of failure criteria.

Parameters	DNV RP-C204 criterion	Germanischer-Lloyd (GL)	Peschmann	Rice-Tracey Cockcroft-Latham (RTCL)	BWH: Bressan-Williams-Hill instability criterion	Liu criterion
Author	D. N. Veritas (2010) [15]	Germanischer Lloyd (2002) [16]	Eike Lehmann, Jörg Peschmann (2010) [17]	Rikard Törnqvist (2003) [18]	Alsos (2008) [19]	Liu (2017) [20]
History of how the criterion is made	-	An empirical criterion is presented by GL to evaluate the critical thru thickness strain at the moment of fracture, where ε_g is the constant strain, ε_e is the necking strain, t is the plate	The maximum strains attained in sheet metal forming before localized necking are called the forming limit strains. The desired shape must be obtained without tearing in sheet metal forming.	Derived analytically based on virtual local necks appearing within significant elements, the RTCL criterion combines two continuum	The Bressan-Williams criterion was initially intended for the positive quadrant of the forming limit diagrams, but the mathematical expression is also valid for	It is proposed to conduct the same simulations for plates modeled with larger mesh sizes (5, 10, 15, and 20t) since while the necking strain is detected easily when a small mesh is

Cont.

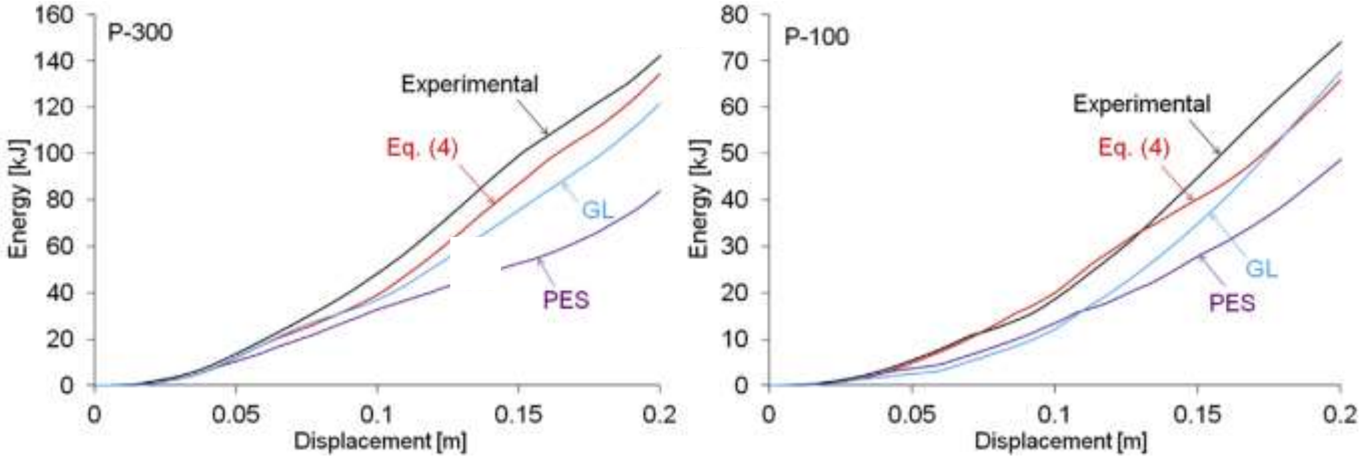
Parameters	DNV RP-C204 criterion	Germanischer-Lloyd (GL)	Peschmann	Rice-Tracey Cockcroft-Latham (RTCL)	BWH: Bressan-Williams-Hill instability criterion	Liu criterion
		thickness, and l_e is the individual element length.	Peschmann experimentally obtained those forming limit diagrams, evaluating the equivalent plastic strain at different locations at the moment of fracture of the damaged ships. Here, t is the plate thickness, l_e is the individual element length, $\alpha = \varepsilon_m \cdot (x_e/t)$ is a factor depending on the necking strain and the length of the neck, and ε_g is the constant strain.	damage models: the Rice-Tracey and Cockcroft-Latham damage mode. Together, they cover the full-stress triaxiality range, defined by hydrostatic stress. Here, ε_n is the failure strain at t/l = 1 at uniaxial stress, and n is the power law exponent for the diffuse necking strain.	negative values. However, as the strain rate ratio becomes negative, the validity of the BW criterion becomes questionable. Hence, the Hill and BW criteria have been combined into one criterion, referred to as the BWH criterion, to cover the full range of β. This new criterion is formulated regarding the strain rate ratio, β.	used (<2t), it is difficult to find the change in the slope of the curve 'strain' versus 'displacement' when a coarse mesh is selected (>5t). Consequently, a different methodology is required to capture this localized strain concentration for a finite element model discretized with a large mesh.

On the other hand, the response of Peschmann and Germanischer Lloyd improves when a sharper indenter is used. The failure criteria are also affected by the mesh size used, Figure 3. As shown in Figure 3b, the failure strain occurred at 0.27, 0.34, and 0.39 for the Germanischer Lloyd (GL), Peschmann, and RTCL criteria, with 2.5 mm mesh size, respectively. The simulation using the coarser mesh of 10 mm appears to produce rupture strains at 0.11, 0.15, and 0.25, respectively.



(a) (b)

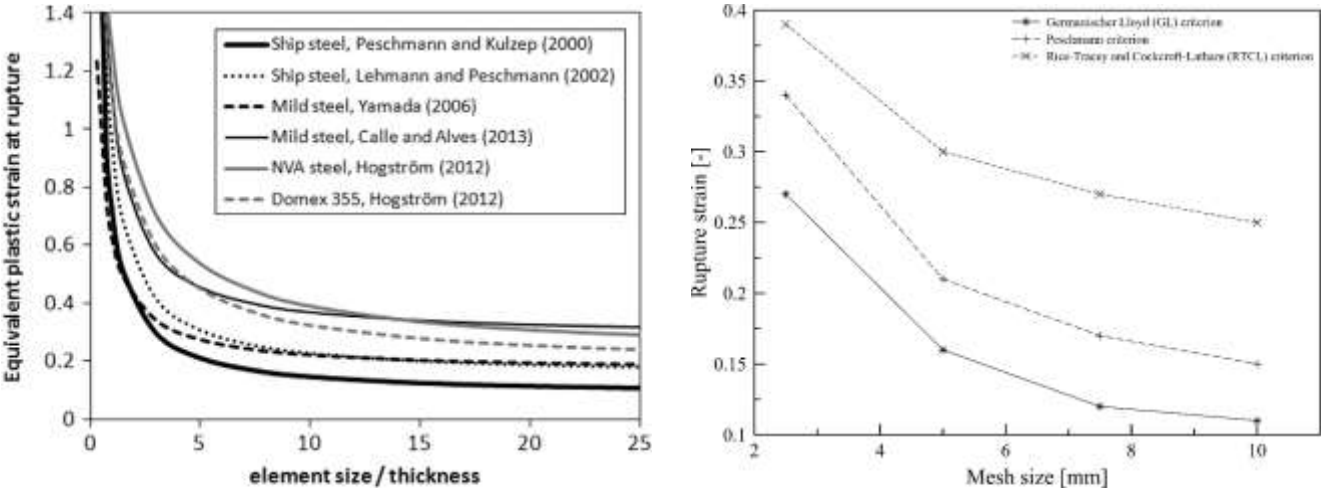
Figure 1. (a) Failure strain with Liu criterion for coarse meshes [20], (b) Force-displacement response using different element sizes [20].



(a) (b)

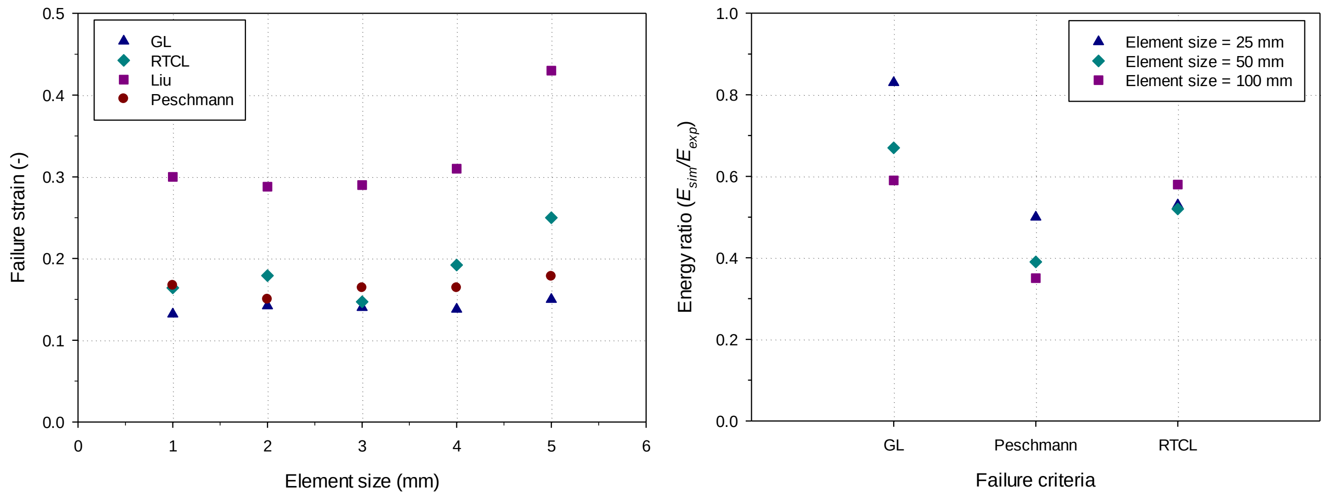
Figure 2. Energy-displacement curves for (a) Specimen P-300 [18] and (b) Specimen P-100 [20]. Comparison of Liu criterion with Peschmann and Germanischer Lloyd; the element size is 9t [20].

The study conducted by Prabowo et al. [26] was aimed at assessing the failure strain under different failure criteria. The researchers compared the results obtained using four different failure criteria: Germanischer Lloyd (GL), Peschmann, Rice-Tracey, Cockcroft-Latham (RTCL), and LIU. Figure 4a was used to present the results of the study. The study showed that the failure criteria selection significantly impacted the failure strain's value. Specifically, the LIU criterion resulted in a much higher value of failure strain (0.417) than the other criteria evaluated, including Germanischer Lloyd (GL) (0.157), Peschmann (0.190), and Rice-Tracey and Cockcroft-Latham (RTCL) (0.289). These results suggest that the LIU criterion may be more suitable for assessing failure strain than the other criteria, particularly in scenarios where high failure strain values are expected. However, it is essential to note that the study's results may not apply to all scenarios. Further research is needed to determine the most suitable application failure criteria. Nonetheless, the study highlights the importance of carefully selecting the appropriate failure criteria for accurate and reliable analysis of structures.



(a) (b)

Figure 3. Variation of the critical failure strain used for FE simulations as a function of the mesh size. (a) Simulation by Calle and Alves [2]; (b) Simulation by Prabowo et al. [28].



(a) (b)

Figure 4. Effect of the element size to failure criteria (a) failure strain (data based in [26]) and (b) energy ratio E_{sim}/E_{exp} (data based in [14]).

In the study of ship collisions, the Energy ratio E_{sim}/E_{exp} is a key parameter used to evaluate the accuracy and reliability of the test models [14], Figure 4b. This ratio compares the simulated energy of the collision, E_{sim}, with the experimental energy of the collision, E_{exp}. The Energy ratio is an essential metric for assessing the performance of the models since it indicates the degree to which the model's predictions match the actual behavior of the ship during a collision. The benchmark study conducted by Ehlers et al. (2008) [14] reported on the test models' Energy ratio E_{sim}/E_{exp}. This study aimed to evaluate the accuracy of the models in predicting the behavior of ships during collisions, and the Energy ratio was a crucial factor in determining the reliability of the models. The study's results provided valuable insights into the performance of the different models, which can be used to improve the accuracy and effectiveness of ship collision simulations in the future.

The use of failure criteria in analyzing structures has become increasingly popular due to its simplicity and CPU efficiency. Its easy implementation into finite element codes makes it an attractive choice for analyzing structures with limited material and failure data. This has made it a valuable tool in various applications, including crashworthiness analyses, accidental analysis involving large-scale ship structures, and simple estimations on forming operations [19]. However, since different failure criteria were introduced in different years, there has yet to be a comprehensive comparison of the characteristics of each criterion in one scenario. Thus, it is necessary to conduct future research to compare each failure criterion in a ship collision scenario to determine which criterion is the most suitable for this application. This comparison will help determine the most efficient and accurate failure criterion for analyzing the structures involved in a ship collision, which is crucial for ensuring the ship's and its passengers' safety. Therefore, it is essential to continue to investigate and develop failure criteria to improve the safety and reliability of structures.

4 Conclusions

Previous researchers developed failure criteria to capture the resulting response due to collision and grounding in the simulation of the catastrophe of ship collision and grounding, which is very complex. The most widely used failure criteria are the DNV RP-C204 criterion, Germanischer Lloyd criterion, Peschmann, Rice-Tracey, Cockcroft-Latham, BWH: Bressan-Williams-Hill instability criterion, and Liu criterion, as the resulting response can be in the form of energy generated during the collision and also in the form of hull damage to the ship. The DNV RP-C204 criterion, Germanischer Lloyd, Peschmann, and Liu will give failure strain values of 0.15, 0.164, 0.26, and 0.45, respectively, as shown in this study, using an element length of 10 mm and a plate thickness of 2 mm in the ship collision simulation. When conducting a simulation analysis on a ship structure, the choice of failure criteria is a critical aspect that needs to be carefully considered. The decision regarding failure criteria should be based on the simulation's specific requirements and the analysis's goals. This is because different failure criteria will have different levels of sensitivity and accuracy in detecting various types of failure modes.

In some cases, it may be necessary to use multiple failure criteria to ensure that all potential failure modes are adequately considered. This is particularly true in applications such as crashworthiness analyses of the ship structure or accidental analysis involving large-scale ship structures. By using multiple failure criteria, engineers can more confidently evaluate the safety and reliability of the ship structure, which is essential for ensuring the protection of human lives and the prevention of environmental disasters.

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