Collapse response analysis of a ship's hull girder in cyclic focused waves using a hydro-elasto-plastic beam model

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ABSTRACT: Large waves and whipping effects cause cyclic bending moments on the hull girder that may cause some regions of the structure to exceed the linear limit. In this event nonlinear structural damage/defect (e.g., plasticity and buckling deformation) is accumulated in the structure, which subsequently degrades the ultimate / post-ultimate capacity of the girder. A cyclic load-shortening curve model has been proposed to track the response of stiffened panels under cyclic loading considering the cumulative degradation due to elastoplastic buckling. Separately, a coupled hydrodynamic FE/Smith method (HFS method) has been developed to predict post-collapse response of the hull girder in waves. In this paper the cyclic load-shortening curve is incorporated into HFS method and verified through a case study example. A container ship is excited in a series of focused waves that causes a cyclic response beyond the hull-girder ultimate strength. The effect of different load-shortening curve models on the post-ultimate response of the girder are studied. These show the sensitivity of the reduced hull girder capacity. The results imply that even if the hull-girder collapse stops with partial damage, the hull-girder capacity could be reduced by the cyclic plasticity and the collapse could rapidly progress in subsequent waves.

1 INTRODUCTION

Within the last decade several catastrophic accidents of ship structural failure under longitudinal bending have occurred. The container ship MOL Comfort broke into two around her midship section in the Indian Ocean in 2013 (Committee on Large Container Ship Safety 2015). The longitudinal bending collapse occurred in a hogging condition. The crew could evacuate the ship because she kept floating even after the collapse providing enough time to deploy lifeboats before sinking. In 2021 the general cargo ship Arvin suffered a catastrophic bending collapse in the Black Sea whilst at anchor (Mentor Marine Consultants 2021). The overall seaworthiness of this vessel is unclear, but the failure itself was captured on a crew video and showed structural failure in accordance with progressive collapse theory in the midship region. The ship almost immediately sank, leading to the loss of six crew lives.

Subsequent surveys of the MOL Comfort sister ships found residual buckling deformation in their bottom panels. One of the possible causes for this residual buckling deformation is that the applied bending moment on the hull girders had occasionally exceeded the hull-girder capacity, but with a short load duration characteristic of a whipping response. This means the structural response, in terms of deformation, did not reach a large magnitude. Therefore, the ships did not exhibit catastrophic collapse, but instead returned to an otherwise normal state except that the plastic deformation accompanied by the buckling remained in the bottom structure where the largest compressive loads had occurred.

In a broader context, this possible scenario implies that ships can appear structurally intact and continue usual operations even if their load history includes short duration occurrences of peak longitudinal bending moments that exceed the ultimate capacity. However, the consequence of these peak loads is the accumulation of plasticity and associated elasto-plastic buckling deformations in critical areas of the hull structure such as the midship double bottom. The reduced structural capacity in these local areas may have a significant detrimental effect on the overall hull girder capacity. These are not accounted for within current partial safety factor driven design methods.

The present study addresses this issue using a newly adapted numerical simulation method to predict post-collapse behaviour/response of the hull-girder in a series of focused waves including cyclic elasto-plastic buckling effects. The adaptation builds on a previously developed hydro-elasto-plastic beam model by Ko et al. (2018; 2020) to predict the dynamic collapse behaviour of a hull girder in waves.

The method uses a beam finite element model coupled with strip theory to predict the hydrodynamic load and bending deformation of a segmented hull form in the time domain. Meanwhile the nonlinear progressive collapse behaviour of each girder segment is calculated according to the Smith method (Smith 1977), which provides the instantaneous internal reaction force of each hull segment at each time increment. This method is named 'Hydrodynamic FE/Smith method' (HFS method).

The Smith progressive collapse calculations within the HFS method are further extended to deal with cyclic effects, using a previously developed method by Li et al. (2019; 2020) to estimate average stress-average strain relationship of plates and stiffened panels under cyclic tension and compression. The proposed method represents the post-collapse behaviour under cyclic loading by a piecewise linear curve while considering the effect of cyclic plasticity/buckling. This shows a likeness to the Bauschinger effect.

2 MODEL FOR ANALYSIS

2.1 *FE/Smith method*

The Smith method has been widely used to analyse progressive collapse behaviour of hull-girder cross sections. The cross section is divided into plate/stiffened panel elements and average stress-average strain curves under uniaxial tension/compression are applied to the elements. The progressive collapse behaviour of the cross section is analysed by giving curvature to the cross section while considering shift of the neutral axis due to effect of buckling and yielding.

The Smith progressive collapse analysis can be incorporated into a thin-walled beam finite element (FE). The key is that the average stress-average strain curves are converted to average stress-average 'plastic' strain curves and applied to integration points on the beam cross section which correspond to the plate/stiffened panel elements in the Smith method. This means the progressive collapse behaviour of the hull-girder cross section is treated as material hardening/softening behaviour of the beam element. Since the FE/Smith method performs the progressive collapse analysis according to Smith's method within the framework of the finite element method, it can be extended to various load conditions other than static bending, such as combined bending and lateral load (Tatsumi & Fujikubo 2020) and dynamic load (Ko et al. 2018).

2.2 *Hydrodynamic FE/Smith method*

The FE/Smith method was extended to analyse dynamic collapse behaviour of the hull girder under impulsive bending load (Ko et al. 2018; Ko et.al. 2020). Recently, dynamic collapse response of the hull-girder in extreme waves has been analyzed based on the FE/Smith method, which is named 'Hydrodynamic FE/Smith method' (HFS) (Shimiya et al. 2021). In the HFS, the hull girder is idealized by a beam model mounted on restoring springs as shown in Figure 1. The equation of motion for the discretized beam model at time $t + \Delta t$ is represented as

$$[M]\{\ddot{u}\}^{t+\Delta t} + [C]\{\dot{u}\}^{t+\Delta t} + [K_r]\{u\}^{t+\Delta t} + \{Q\}^{t+\Delta t} = \{F\}^{t+\Delta t} \tag{1}$$

where $[M]$ = vertical mass matrix; $[C]$ = hydrodynamic and structural damping matrix; $[K_r]$ = restoring stiffness matrix; $\{Q\}$ = internal force vector; $\{F\}$ = external force vector; $\{\ddot{u}\}$ = acceleration vector; $\{\dot{u}\}$ = velocity vector and $\{u\}$ = displacement vector. $\{Q\}$ is calculated according to Smith's method. The established strip theory is adopted to estimate hydrodynamic forces. Radiation force is considered in the left-hand side of Equation (1), that is added mass and wave damping coefficient which are calculated by 2D-BEM and included in $[M]$ and $[C]$. $\{F\}$ consists of the wave exciting force and scattering force. The scattering force is derived from the added mass and the wave damping coefficient based on the New Strip method (Kitagawa & Kashiwagi 2019).

The HFS can consider so-called geometric nonlinearity of the hydro-static/dynamic force by preparing tables of the added mass, the wave damping coefficient, the diffraction force and the restoring spring for each draft in advance. If impulsive load is applied to the beam model, the HFS can deal with whipping response as well. However, in the present study, the hydro-static/dynamic force is assumed completely linear to simplify the problem and focus on the effect of cyclic buckling and plasticity on the hull-girder collapse in waves.

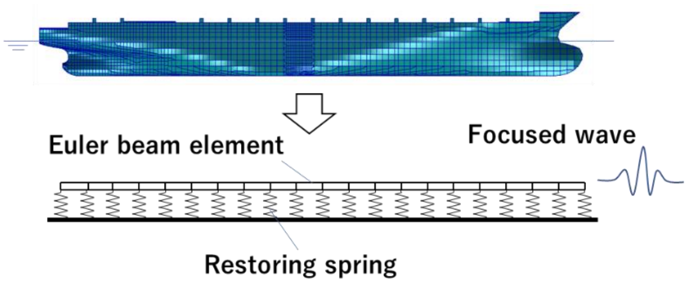


Figure 1. Beam finite element model used in hydrodynamic FE/Smith method (HFS).

2.3 *Cyclic load-shortening curve*

There have been numerous studies which deal with the load-shortening curve (average stress-average strain curve) of stiffened panels under monotonic compression. Yao & Nikolov (1991) developed an analytical method to estimate average stress-average strain curve of the plates and stiffened panels subjected to uniaxial compression. Gordo & Soares (1993) derived empirical formulae of the average stress-average strain curves, which are adopted in the Common Structural Rules for Bulk Carriers and Oil Tankers (IACS). Note that: while the Gordo method and IACS method are principally the same, different effective width models are implemented in these methods.

Large amplitude cyclic bending of the hull girder causes corresponding in-plane cyclic shortening of stiffened panels in the deck and double bottom regions. Numerical simulations (Cui and Ding, 2022; Li et al., 2019; Yao and Nikolov, 1990) and experiments (Xu et al., 2022; Cui and Yang, 2018) have shown that cyclic loads that exceed the ultimate strength of the panel demonstrate a distinct nonlinear unloading/reloading pattern and a reduction in strength capacity in subsequent cycles.

Recognising this pattern, a practical algorithmic model was developed to estimate average stress-average strain curve of the plates and stiffened panels under cyclic loading (Li et al. 2019; Li et al. 2020). The proposed method needs a base curve of the average stress-average strain relationship under monotonic loading which can be estimated by some other method like NFEM or CSR. The average stress-average strain curve during unloading/re-loading is modelled by a piecewise linear curve which is controlled by two parameters. The two parameters are adjusted so that the hysteresis curve fit to experimental or numerical simulation results.

This cyclic average stress-average strain algorithm is adopted to simulate hull-girder collapse response in cyclic focused waves. In the original cyclic model, the unloading stiffness after compressive ultimate strength is slightly reduced in the region the average stress is compressive as shown in Figure 2, but that is neglected in the present study for simplicity. On the other hand, stiffness reduction in the tension side is considered in the hull-girder collapse simulation by the HFS. Although this stiffness reduction includes both contributions of cyclic plasticity like Bauschinger effect and release of the elastic buckling deformation, it is assumed that the stiffness reduction results only from the former. It means that the elastic stiffness is assumed constant during the process of the hull-girder collapse.

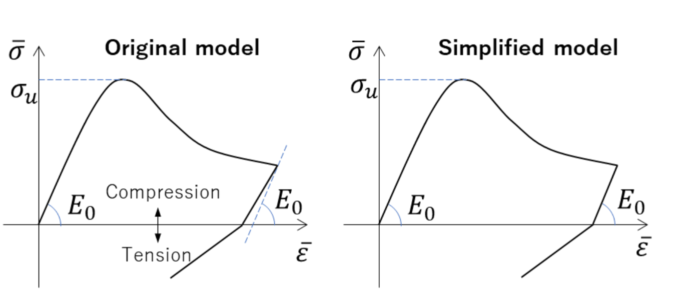


Figure 2. Cyclic load-shortening model and simplification for unloading stiffness.

3 CASE STUDY

3.1 *Subject ship*

A 5,250TEU container ship is taken as a subject ship. The principal dimension of the subject ship is listed in Table 1. The subject ship is discretised into 40 beam elements as shown in Figure 3. A total of 11 types of the cross section are assigned to each beam element. The discretized beam model does not represent the real hull shape especially around fore-and-aft parts because the available data of the subject ship is limited, but it is sufficient to investigate the fundamental nature of the collapse response of the hull girder in focused waves.

Table 1. Principal dimension of the subject ship.

Length	267 m
Breadth	39.8 m
Depth	23.6 m
Draft (Full load condition)	14 m
Dead weight	68,940 ton

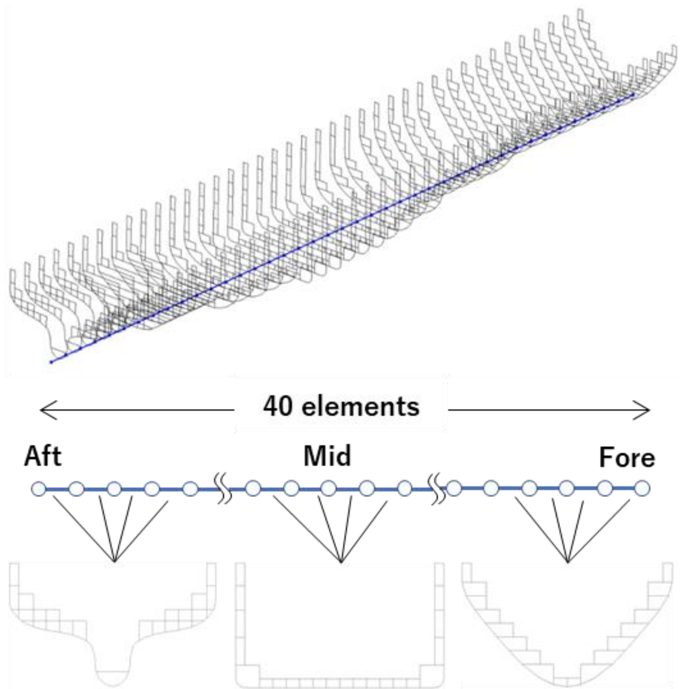


Figure 3. Discretization of the subject ship into beam elements.

3.2 *Cyclic focused waves*

An episode of a focused wave is derived by First Order Reliability Method (FORM) (Jensen 2008) in which the ISSC wave spectrum is used. The mean wave period is set to be 13 sec. A cyclic focused wave is derived by repeating the same focused wave, i.e., simply connecting the subsequent wave episode to the first wave episode. An example of the sequence of a series of two focused waves is shown in Figure 4. The wave elevation is normalized by the maximum value. This wave episode is designed so that the maximum hogging moment is induced in the midship section around 50 and 150 sec. Since the aim of this study is to reveal the post-collapse response of the hull girder, the applied bending moment is assumed to exceed the ultimate capacity of the hull girder. The magnitude of the wave amplitudes is adjusted so that the maximum bending moment attains the prescribed value.

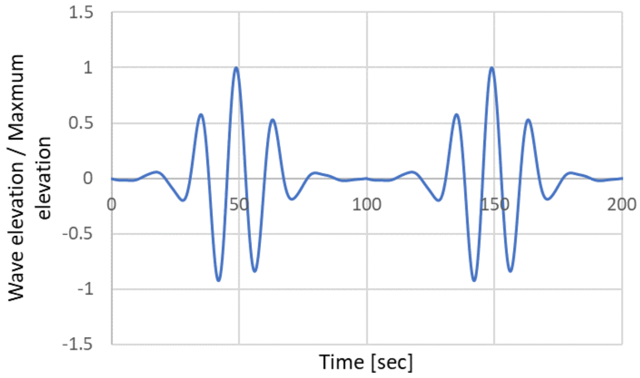


Figure 4. Designed cyclic focused waves.

3.3 *Analysis condition*

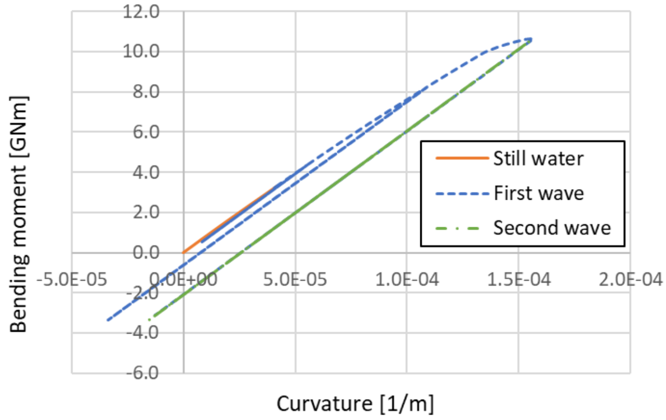
The CSR average-stress-average strain curve originally proposed by Gordo & Soares (1993) is adopted as the base curve. The updating rule of the average-stress-average strain curve after unloading follows the authors' model (Li et al. 2019). As mentioned in section 2.3, the reduction of the unloading stiffness in the compression side is disregarded.

Before applying the focused wave, a still-water load corresponding to a full-loading condition is applied to the hull girder. This induces a large hogging moment around the midship which is about 32% of the ultimate hogging strength of the subject ship. Next, the two cyclic focused waves of total 200 sec (Figure 4) are applied where the amplitudes of the focused waves are linearly adjusted so that applied hogging moment including the still-water component exceeds the ultimate hogging strength by 1.0%. The nonlinearity of hydro-dynamic/static force is not considered.

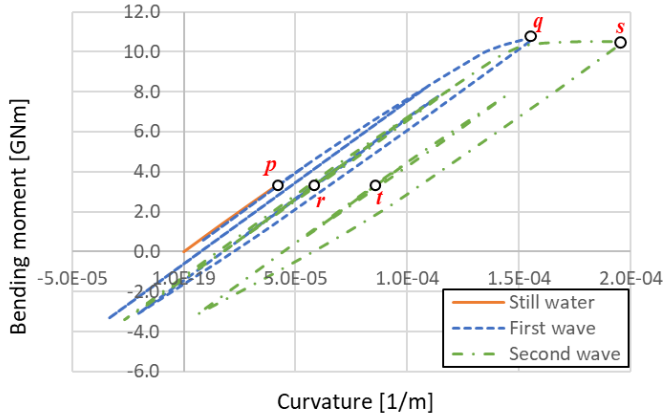
3.4 *Results and discussion*

Figure 5 shows bending moment-curvature relationships of collapsed cross sections of the hull girder under the cyclic focused waves. The original CSR curve is used as the average stress-average strain relationships of the plate/stiffened panels element in (a) while the proposed cyclic average stress-average strain curve in (b). In terms of sign convention, the hogging moment is taken as positive in these figures.

In Figure 5(a), the hogging moment is linearly increased up to about 32% of the hogging ultimate strength by still-water loading, and then further increased by the first focused wave. The bending stiffness starts to decline due to the buckling and yielding and the hull girder attains the ultimate strength. However, the exceedance of the bending moment to the ultimate capacity is small (1.0%) and the deformation is not developed much, and the bending moment is unloaded immediately. Even when the second focused wave acts on the hull girder subsequently, it is within the elastic region and the deformation is not increased at all. This result coincides with the previous literature (Iijima et al., 2015) and would be because the still-water hogging moment is reduced by the hogging residual deformation due to the first focused wave.



(a) No cyclic plasticity (Original CSR).



(b) Cyclic plasticity (CSR + Proposed model).

Figure 5. Bending moment-curvature relationships under the two cyclic focused waves.

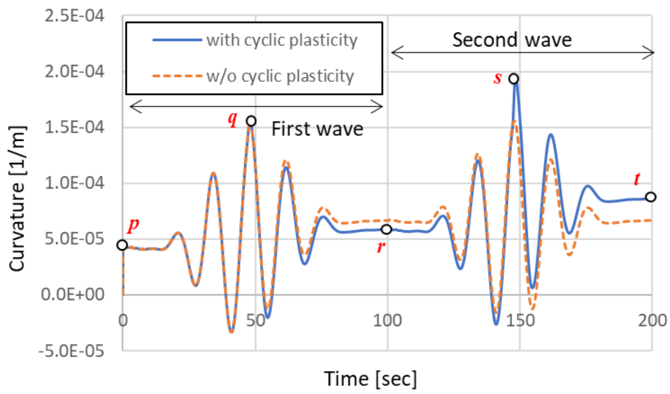


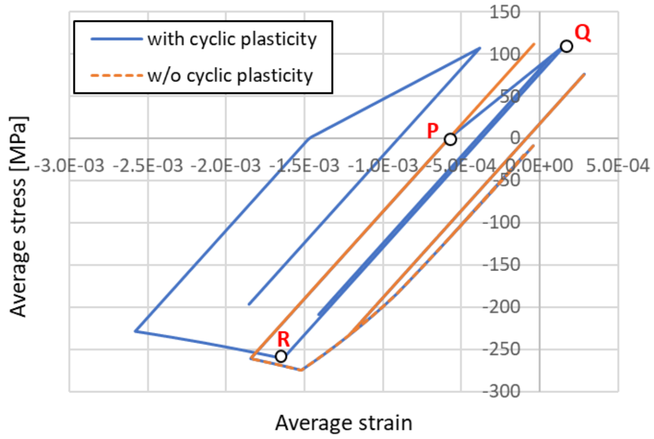
Figure 6. Time history of curvature at the collapsed element under the two cyclic focused waves.

On the other hand, when the cyclic average stress-average strain curve model is used, the bending deformation is induced by the second wave as shown in Figure 5 (b) (From the point *q* to *s*). The deformation increase can be also confirmed in comparison to the curvature time histories shown in Figure 6. The points *p, q, r, s* and *t* in Figure 6 are corresponding to those in Figure 5 (b). The curvature in considering the cyclic model is smaller at the end of the first focused wave (the point *r*), but it is increased by the peak hogging load in the second focused wave (the point *s*), and the residual curvature is eventually larger (the point *t*).

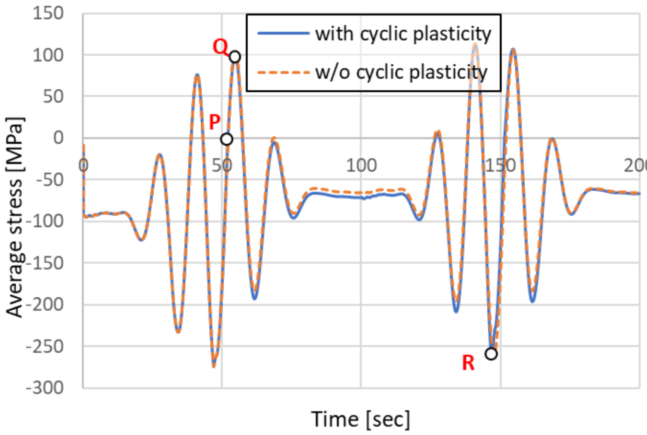
Figure 7 compares responses of the average stress and average strain of a bottom stiffened panel of the collapsed cross section. When the cyclic model is used, the unloading stiffness is reduced by the first focused wave (the process P-Q in Figure 7 (a) and (b)). Therefore, the average compressive strain at the end of the first wave (= residual compressive strain after the first wave) is smaller than without the cyclic model as shown in Figure 7 (c), which results in the smaller curvature after the first wave in Figure 6 as described above. On the other hand, Figure 7 (b) indicates that the residual compressive stress after the first wave is slightly larger than without the cyclic model. This is partially because the residual hull-girder curvature after the first wave becomes smaller due to the reduction of unloading stiffness and the reduction of still-water hogging moment explained above becomes smaller. Therefore, when the hull girder encountered the second focused wave, the applied load exceeds the residual compressive capacity again at the point R, which results in the increase of the deformations.

These results indicate that the post-collapse response of the hull girder in waves is very sensitive to the cyclic plasticity of the stiffened panels. Although the result is not shown in this paper, when the applied load is increased up to 2.5% larger than the ultimate hogging strength, the hull-girder deformation does not increase much in the first focused wave similar to Figure 5 (b), but the catastrophic collapse is induced in the second one. When the applied load is 5 % greater than the ultimate strength, the first focused wave is enough large to induce the catastrophic bending collapse. The effect of the cyclic collapse behaviour of the stiffened panels on the global collapse response of the hull girder would be more important when the whipping response is accompanied since the hull-girder collapse is more likely to stop due to its short duration. In addition, the behaviour of the stiffened panels under the catastrophic hull girder collapse should be revealed. The plastic deformation is localized during the process of the collapse, and the induced high plastic strain leads ductile damage and fracture in the stiffened panel structures. Hence, it would be worth investigating mechanism of the ductile damage initiation and propagation of the stiffened panels accompanied by the buckling, which would be helpful to develop a criterion of tolerable deformation in the post-collapse regime.

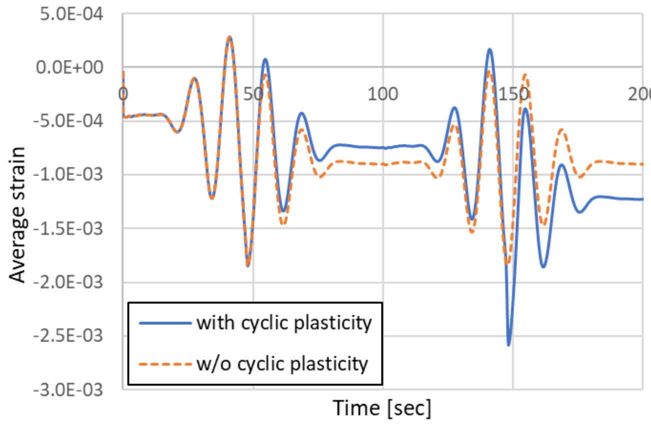
The proposed hydro-elasto-plastic beam model considering the effect of cyclic plasticity can finish a simulation like Figure 5 in several minutes and has the potential to clarify the post-collapse response of the hull-girder in waves. The proposed method would be useful in risk-based design of the ship structure targeting the hull-girder bending collapse.



(a) Average stress-average strain relationships.



(b) Average stress time histories.



(c) Average strain time histories.

Figure 7. Average stress and average strain of a bottom stiffened panel in the collapsed element.

Although the current study verifies the ability of the model to account for cyclic plasticity, validation of the proposed method is lacking in the present study. Specifically, the cyclic collapse behaviour of the stiffened panels should be further investigated because the adopted cyclic curve model has been calibrated in higher strain ranges (Li et al. 2019). The contribution rate from the cyclic plasticity and the residual elastic buckling to the unloading stiffness reduction are issues that will influence the results from the proposed model. Ultimately, more advanced and precise simulations like CFD/FEM coupling approach might be needed to validate the proposed hydro-elasto-plastic approach. These remain future works.

4 CONCLUSIOIONS

A hydro-elasto-plastic beam model is developed to predict the hull-girder collapse response in focused waves by implementing a cyclic average stress-average strain curve model into the Hydrodynamic FE/Smith method. The hull-girder collapse response of a container ship in a series of focused waves is simulated by the proposed method. The key findings are summarised as follows.

- When the average stress-average strain curve model is 'not' used, the hull-girder bending deformation is no longer developed by the subsequent focused wave. This is because the residual hull-girder deformation due to the first focused wave reduces the still-water bending moment.
- By considering the effect of cyclic plasticity, the hull girder bending deformation is increased in the subsequent focused wave. It implies that even if the hull-girder deformation stops with partial failure, the collapse could rapidly progress in subsequent waves.

The results indicates that the post-collapse behaviour of the hull girder is sensitive to the cyclic average stress-average strain curve. Continued efforts on the validation of the average stress-average strain curve via more advanced and extensive numerical simulation and experimental data are required to improve the confidence in the results and will become the future research subjects.

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