論 文

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과도 인장변형효과를 고려한 개선된 이상화구조요소

백점기*

Advanced Idealized Structural Units Considering the Excessive Tension-Deformation Effects

by

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요 약

본 논문에서는 구조전체의 최종붕괴강도에 대한 국부 구성부재의 과도인장변형효과를 고려하기 위하여 기존의 이상화구조요소들, 즉 이상화 보-기둥요소, 이상화 판요소 및 이상화 보강판요소의 적용범위를 확장하며, 이를 위해 간이 역학적모델을 제시한다. Leander급 Frigate함의 1/3 축척 선각구조모형에 대해 Dow가 수행한 최종 종강도실험결과와 본 해석결과를 비교한 결과, 압축에 의한 구조부재의 파손 뿐만아니라 과도인장변형에 의한 파손도 구조전체적인 붕괴거동, 특히 붕괴후 거동에 크게 영향을 미침을 알 수 있었다.

Abstract

In this paper, the extent of use of three kinds of the existing idealized structural units, namely the idealized beam-column unit, the idealized unstiffened plate unit and the idealized stiffened plate unit, is expanded to deal with the excessive tension-deformation effects, in which a simplified mechanical model for the stress-strain relation of steel members under tensile load is suggested. The 1/3-scale hull model for a leander class frigate under sagging moment tested by Dow is analyzed, and it is shown that the excessive tension-deformation is a significant factor affecting the progressive collapse behavior, particularly in the post-collapse range.

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1. Introduction

When the safety of a ship structure is considered, the analysis of the ultimate collapse behavior for the whole structure is essential. To predict the maximum load-carrying capacity, the analysis may be performed up to the ultimate collapse state. However, the post-collapse behavior should also be analyzed to estimate the absorbed energy capacity which is calculated by integrating the area below the load-displacement curve for the structure[1].

So far, to analyze the progressive collapse behavior of a ship structure using the idealized structural unit method(ISUM), several idealized structural units[1], [2], [3] have been developed taking into account ductile-collapse behavior. In these units, however, the importance for an excessive tension-deformation behavior after yielding has been disregarded.

As sagging moment increases for instance, deck structure will collapse by compression, while excessive tension-deformation will be formed at bottom part. It is considered that the overall collapse behavior of a ship's hull is dependent on tension-deformation behavior as well as ductile-collapse behavior due to axial compression or shearing force.

In this paper, the extent of use of three kinds of the existing idealized structural units, namely the idealized beam-column unit, the idealized unstiffened plate unit and the idealized stiffened plate unit is expanded to deal with the excessive tension-deformation effects. For this purpose, a simplified mechanical model for the stress-strain relation of steel members under tensile load is suggested.

The 1/3-scale hull model of a leander class frigate under sagging moment tested by Dow[4] is analyzed using the present theory, and it is observed that the tension-deformation of individual members plays a important role on the progressive collapse behavior, particularly in the post-collapse range of the whole structure.

2. Theoretical Formulation

Since the detailed formulation for the idealized structural units including the ductile-collapse behavior due to axial compression and shear is found in the previous papers[1], [2], [3], only brief description and additional formulation are given here.

2.1 Basic Idealizations

(1) ISUM Modelling for Ship Structure

In ISUM modelling, the basic structural member composing the object structure is chosen as the idealized structural unit.

Heavy longitudinal and transverse members supporting plate panels are modelled as the idealized beam-column unit which has only two end nodal points, shown in Fig. 1 In a stiffened panel, a number of one-sided stiffeners are at-

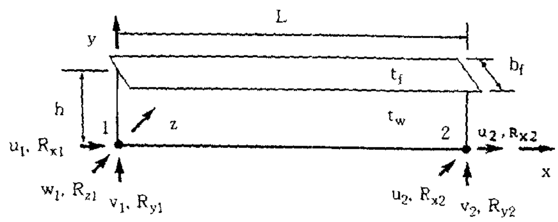

Fig. 1 The idealized beam-column unit

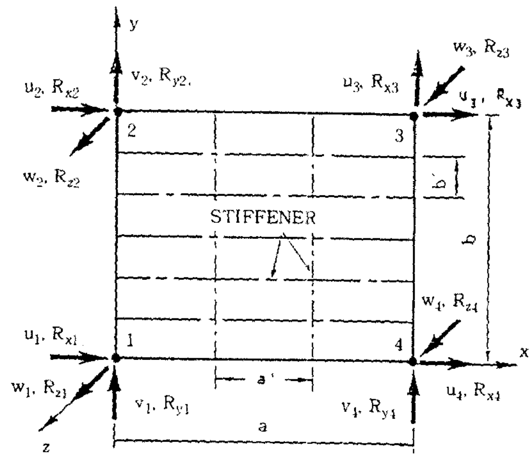

Fig. 2 The idealized stiffened plate unit

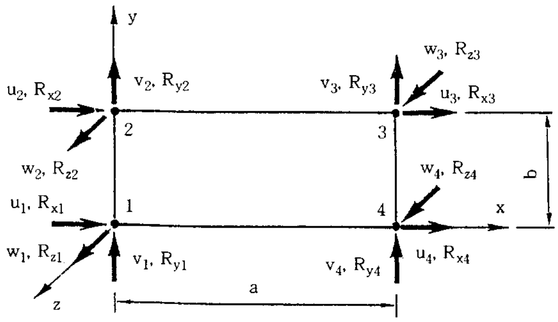

Fig. 3 The idealized unstiffened plate unit

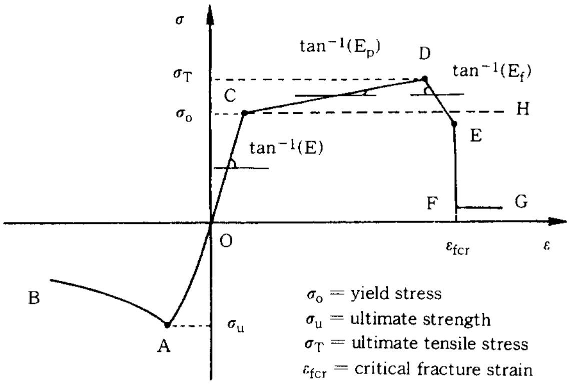

Fig. 5 Idealization of nonlinear behavior for steel members

tached to the plate in the longitudinal and/or transverse directions. The stiffener spacing is usually equal and geometric/material properties of each stiffener are supposed to be the same in each direction. The stiffened panel is modelled as the idealized stiffened plate unit, indicated in Fig. 2 Also when the panel has no stiffener, it is modelled as the idealized unstiffened plate unit, shown in Fig. 3 The idealized unstiffened and stiffened plate units have only four corner nodal points.

(2) Idealization of Structural Behavior

If a structural member is subjected to axial compression or shearing force, it will buckle with increase in the applied load and show large deflection behavior. As a result, its in-plane stiffness decreases and it reaches the ultimate collapse state. In the post-collapse range, the internal stress goes down if the compression-deformation is continued.

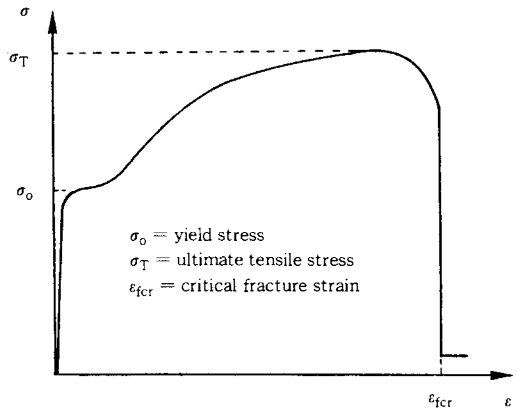

Fig. 4 A typical tensile test result for steel material

On the other hand, when a member is subjected to a tensile load, its behavior is different from that of compressed members. Fig. 4 represents a typical stress-strain curve for steel member under tensile load. It is observed that as the tensile load increases the member yields without lateral deflection. In the existing idealized structural units, behavior of the yielded unit has been treated as the dotted line(segment CH) in Fig. 5 Because of the strain-hardening effect, however, the member can carry further loading even after yielding and reaches the ultimate tensile strength. When there is an excessive tension-deformation, the actual cross-sectional area decreases and the nominal stress goes down with increase in the tension-deformation. After that, the ductile fracture will occur if the tensile strain of the member exceeds the critical fracture strain which depends on material properties, initial crack damage and so on.

In this paper, the actual stress-strain curve for structural members is idealized as the solid line in Fig. 5 Then if the characteristics of each segment in Fig. 5 are known, the stress-strain curve can be traced as :

(i) Compressed Member :

OA(Elastic Large Deflection Behavior) → A

(Ductile-Collapse Strength) →AB(Post-Collapse Behavior)

(ii) Tensiled Member :

OC(Linear Elastic Behavior) → C(Yield Strength) → CD(Post-Yield Behavior) → D (Ultimate Tensile Strength) → DE(Post-Tensile Strength Behavior) → E(Ductile-Fracture Strength) → EF-FG(Post-Fracture Behavior)

In the next section, the detailed formulations for each segment or failure criteria are described. Table. 1 indicates the definition of failure modes of the idealized structural units.

Table 1 Definition of failure modes for the idealized structural units

Model No.	Beam-Colum Element	Unstiffened Plate Element	Stiffened Plate Element
0	Failure-Free	Failure-Free	Failure-Free
1	Collapse	Collapse	Local Collapse
2	–	–	Penel Collapse (between trans.)
3	–	–	Penel Collapse (between longi.)
4	–	–	Overall Collapse
5	Yield Strength	Yield Strength	Yield Strength
6	Ultimate Tensile Strength	Ultimate Tensile Strength	Ultimate Tensile Strength
7	Ductile-Fracture	Ductile-Fracture	Ductile-Fracture

2.2 Idealized Beam-Column Unit

(1) General

As mentioned, heavy longitudinal and transverse supporting members are modelled by the idealized beam-column unit, indicated in Fig. 1 End conditions of the unit are assumed to be pin-jointed. When a ship's hull is subjected to a longitudinal bending moment, this unit will carry the axial load.

In the present study, a deflected column is replaced by an equivalent straight unit which has the reduced stiffness due to the existence of lateral deformation. As a result, rotational degree of freedom is not necessary to be included in the numerical formulation. The nodal force increment $\{\Delta R\}_{bc}$ and the nodal displacement increment $\{\Delta U\}_{bc}$ of the unit in the local coordinate are then defined by(see Fig. 1)

$$\{\Delta R\}_{bc} = \{\Delta R_{x1}\ \Delta R_{x2}\}^T \tag{1.a}$$

$$\{\Delta U\}_{bc} = \{\Delta u_1\ \Delta u_2\}^T \tag{1.b}$$

Applying the principle of virtual work, the stiffness equation of the unit will be given by

$$\{\Delta R\}_{bc} = [K]_{bc}\{\Delta U\}_{bc} \tag{2}$$

where [K]bc is the stiffness matrix of the idealized beam-column element in the local coordinate and will change according to failure or loading condition. In the following, [K]bc for each segment in Fig. 5 is formulated.

(2) Segment OA : Elastic Large Deflection Behavior

An initially deflected pin-ended column is considered. The geometric configuration may take the following form :

$$w_o = \delta_o \sin(\pi/L)x \tag{3.a}$$

$$w = \delta \sin(\pi/L)x \tag{3.b}$$

where δ_o = initial deflection amplitude

δ = unknown added-deflection amplitude

L = member length

Applying the principle of minimum potential energy, the unknown will be found.

$$\delta = \frac{\delta_o}{1-R/R_E} \tag{4}$$

where R_E = Euler's buckling load

Using the above solution, total end-shortening considering the large deflection effect will be given by

$$u = \frac{RL}{EA_b} + \frac{\pi^2\delta_o^2}{4L(1-R/R_E)^2} - \frac{\pi^2\delta_o^2}{4L} \tag{5}$$

where A_b = cross-sectional area of the unit

The incremental relationship between the axial force and the end-shortening is then given by

$$\Delta R_x = \eta_E \Delta u \quad (6)$$

where

$$\eta_E = \frac{1}{\dfrac{L}{EA_b} + \dfrac{\pi^2 \delta_o}{2LR_E(1-R/R_E)^3}}$$

Accordingly, considering the equilibrium condition, the stiffness matrix [K]bc in this range will be obtained.

(3) Criterion of Point A : Ductile-Collapse Strength

Several criteria for checking buckling or collapse of the beam-column member have been suggested. In this paper, the well-known Perry-Robertson formula[5] taking into account the initial imperfection effect is used.

(4) Segment AB : Post-Collapse Behavior

For the collapsed unit, the following relationship between the axial force and the end-shortening, using the concept of plastic hinge collapse mechanism can be used[6].

$$\frac{R}{R_p} = \left\{\left[\frac{R_p}{2M_p}\right]^2 Lu + 1\right\}^{1/2} - \frac{R_p}{2M_p}(Lu)^{1/2} \quad (7)$$

where R_p = fully plastic axial load(= $\sigma_o A_b$)
M_p = fully plastic bending moment (= $Z_p \sigma_o$)
Z_p = plastic section modulus
σ_o = yield stress

The incremental form of the above equation will become

$$\Delta R = \eta_u \Delta u \quad (8)$$

where $\eta_u = R_p^3 L/8\{M_p^2[(R_p/2M_p)^2 Lu+1]^{1/2}\} - \dfrac{R_p^2 L}{4M_p(Lu)^{1/2}}$

Accordingly, considering the equilibrium condition, the stiffness matrix [K]bc in the post-ultimate range will be obtained.

(5) Segment OC : Linear Elastic Behavior

In this case, the behavior of the unit is linear and the stiffness matrix will be the same as that of the truss element.

(6) Criterion of Point C : Yield Strength

When the axial stress σ_x reaches the yield stress σ_o, the unit is yielded.

$$\sigma_x \geq \sigma_o \quad (9)$$

(7) Segment CD : Post-Yield Behavior

Even after yielding, the steel member can carry further tensile loading because of the strain-hardening effect. As shown in Fig. 5, the gradient of the stress-strain curve for the yielded unit can be simplified by

$$E_p = \alpha_p E \quad (10)$$

where E = Young's modulus
E_p = tangent modulus of the yielded unit
α_p = coefficient

In the above equation, coefficient α_p can be obtained from the tensile test result. Thus the stiffness matrix in this range will be given by

$$[K]_{bc} = \frac{E_p A_b}{L} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \qquad (11)$$

(8) Criterion of Point D : Ultimate Tensile Strength

If the axial stress exceeds the ultimate tensile stress σ_T, the unit will reach the ultimate tensile strength.

$$\sigma_x \geq \sigma_T \qquad (12)$$

(9) Segment DE : Post-Tensile Strength Behavior

After the axial stress reaches the ultimate tensile strength, the internal stress goes down with increase in the tension-deformation as shown in Fig. 5 The gradient of the stress-strain curve in this range can be simplified by

$$E_f = \alpha_f E \qquad (13)$$

where E_f = tangent modulus in the post-tensile strength range

α_f = coefficient

In the above equation, coeffecient α_f can also be obtained from the tensile test result of the member and the stiffness matrix in this case is given by

$$[K]_{bc} = \frac{E_f A_b}{L} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \qquad (14)$$

(10) Criterion of Point E : Ductile-Fracture Strength

If the axial tensile strain exceeds the critical fracture strain of the unit depending on material property, initial crack and so on, the ductile-fracture will occur.

$$\varepsilon_x \geq \varepsilon_{fcr} \qquad (15)$$

where ε_{fcr} is the critical fracture strain of the unit, which is obtained from the tensile test result. Here, even for an initially cracked unit, ε_{fcr} can be obtained by the tensile test.

(11) Segment EF and FG : Post-Fracture Behavior

If the unit is fractured, it is not able to carry the tensile load further. In the subsequent loading step, therefore, the stiffness matrix of the fractured unit is set to be zero such that the internal stress increment is zero for the rest of the analysis. Also the accumulated stress in the fractured unit should be released [20].

2.3 Idealized Unstiffened and Stiffened Plate Units

(1) General

In the present method, the deflected plate panel is replaced by an equivalent "flat" plate panel which has the reduced in-plane stiffness due to the existence of lateral deformation. As a result, rotational degrees of freedom at each nodal point can be removed as in the idealized beam-column unit. Therefore, the total degrees of freedom at each nodal point are just three axial displacements which are u, v and w in the x, y and z direction, respectively. Thus, the nodal force increment $\{\Delta R\}_{pl}$ and the nodal displacement increment $\{\Delta U\}_{pl}$ in the local coordinate are defined by (see Fig. 2 and 3)

$$\{\Delta R\}_{pl} = \{\Delta R_{x1}\ \Delta R_{y1}\ \Delta R_{z1} \cdots \Delta R_{x4}\ \Delta R_{y4}\ \Delta R_{z4}\}^T$$
$$\{\Delta U\}_{pl} = \{\Delta_{u1}\ \Delta_{v1}\ \Delta_{w1} \cdots \Delta_{u4}\ \Delta_{v4}\ \Delta_{w4}\}^T \qquad (16)$$

Also the average stress increment of the unit is calculated by

$$\{\Delta\sigma\} = [D]\{\Delta\varepsilon\} \tag{17}$$

where $\{\Delta\sigma\} = \{\Delta\sigma_{xav}\ \Delta\sigma_{yav}\ \Delta\tau_{xyav}\}^T$
$[D]$ = average stress-average strain matrix

Applying the principle of virtual work, the stiffness equation of the unit will be given after unbalance forces are eliminated :

$$\{\Delta R\}_{pl} = [K]_{pl}\{\Delta U\}_{pl} \tag{18}$$

where $[K]_{pl}$ = stiffness matrix of the idealized plate unit
$= \int([B_p]^T[D][B_p] + [G]^T[\sigma_b][G])\,dvol$

$$[\sigma_b] = \begin{bmatrix} \sigma_{xav} & \tau_{xyav} \\ \tau_{xyav} & \sigma_{yav} \end{bmatrix}$$

It is observed from the above equation that once the [D] matrix is known, the stiffness matrix of the unit is calculated. In this regard, the following description is focused on the derivation of [D] matrix.

(2) Segment OA : Elastic Large Deflection Behavior

An actual plate member always has initial deflection. When a compressive load is dominant, in-plane stiffness of an initially deflected plate panel decreases from the beginning with the increase in the applied load. Also the present method attempts to replace the deflected plate by an equivalent flat plate accounting for the reduction of in-plane stiffness due to lateral deflection.

(i) Idealized Unstiffened Plate Unit

Using the effective width formulation[8], the [D] matrix of deflected plate units is given by :

$$[D] = [D]^B_{pl} \tag{19}$$

where $[D]^B_{pl}$ is the stress-strain matrix for the deflected plate panel.

(ii) Idealized Stiffened Plate Unit

It is assumed that stiffeners keep straight until they buckle and thus the stress-strain matrix is calculated by adding the deflected plate and intact stiffeners as [3] :

$$[D] = [D]^B_{sp} = [D]^B_{pl} + [D]^{EXY}_{st} \tag{20}$$

where

$$[D]^{EXY}_{st} = \begin{bmatrix} En_{sx}A_{sx}/bt & 0 & 0 \\ 0 & En_{sy}A_{sy}/at & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

n_{sx} = number of longitudinal stiffeners
n_{sy} = number of transverse stiffeners
A_{sx} = cross-sectional area of one longitudinal stiffener
A_{sy} = cross-sectional area of one transverse stiffener
a = plate length
b = plate breadth
t = plate thickness

(3) Criterion of Point A : Ductile-Collapse Strength

Considering the membrane stress distribution of deflected plate elements under applied loads, the ductile-collapse criteria are as follows :

(i) Idealized Unstiffened Plate Unit

The equivalent stress in the corner or the transverse mid-edge or the longitudinal mid-edge of the unit reaches the yield stress, the unstiffened plate unit will be assumed to collapse [13].

(ii) Idealized Stiffened Plate Unit

Collapse patterns for stiffened plate panels are divided into three sorts such as local collapse, panel collapse and overall collapse[5]. Here, the local collapse of plate part between stiffeners is checked by using the same criterion for the unstiffened plate unit. Also the panel and overall collapse is treated as an buckling problem of columns with effective breadth [1].

If longitudinal stiffeners collapse while transverse stiffeners are still intact, the panel collapse between transverse stiffeners will occur. On the other hand, if transverse stiffeners collapse while longitudinal stiffeners are still intact, the panel collapse between longitudinal stiffeners will occur. Also if both longitudinal and transverse stiffeners collapse at the same time, then the overall collapse occurs.

For checking the collapse of stiffener with effective breadth, several formulas have been suggested[15]. In the present study, the well-known Perry-Robertson formula is employed, as in the idealized beam-column unit. It should be noted that the present idealized stiffened plate unit does not take into account the flexural-torsional collapse pattern of stiffeners.

(4) Segment AB : Post-Collapse Behavior

After the unit collapses under axial compression, the internal stress goes down if the compression-deformation is continued. General formulations of the stress-strain relation in this range have been described by the autor[3] or Ueda et al[14]. However, a more simplified derivation is made as follows :

(i) Idealized Unstiffened Plate Unit

The equivalent stress of a collapsed unit should keep constant and the change of membrane stress components in the unit may be negligible as far as the loads are applied continuously. The average membrane strain components of the collapsed unit are calculated with the assumption that the poisson's ratio effect of the collapsed unit is neglected.

$$\varepsilon_{xav} = \sigma_{xmax}{}^{u} / E \qquad (21)$$
$$\varepsilon_{yav} = \sigma_{ymax}{}^{u} / E$$

where $\sigma_{xmax}{}^{u}$ and $\sigma_{ymax}{}^{u}$ are maximum membrane stresses just before or after ultimate collapse of the unit in the x and y direction, respectively.

Using the effective width formulation[8], the average membrane stress components of the collapsed unit are obtained by

$$\sigma_{xav} = be / b \ \sigma_{xmax}{}^{u} \qquad (22)$$
$$\sigma_{yav} = be / b \ \sigma_{ymax}{}^{u}$$

where b_e = effective plate breadth
a_e = effective plate length

With the increase in the compression-deformation, the effective plate breadth and length of the collapsed unit also decrease continuously, and it is assumed that the reduction tendency of the effective plate breadth /length with increase in the applied loads is same with that in the pre-collapse range [15], that is,

$$b_e / b = \sigma_{xav}{}^{*} = \sigma_{xmax}{}^{*} \qquad (23)$$
$$a_e / a = \sigma_{yav}{}^{*} = \sigma_{ymax}{}^{*}$$

where the asterisk indicates a virtual amount of the stress.

Under the assumption that initial imperfection effect, Poisson's ratio effect and aspect ratio effect are neglected for the collapsed unit, the virtual maximum stresses are calculated by [16]

$$\sigma_{xmax}{}^{*} = 2\sigma_{xav}{}^{*} - \sigma_{xcr} = E\varepsilon_{xav}{}^{*} \qquad (24)$$
$$\sigma_{ymax}{}^{*} = 2\sigma_{yav}{}^{*} - \sigma_{ycr} = E\varepsilon_{yav}{}^{*}$$

where σ_{xcr} = buckling stress in longitudinal compression
σ_{ycr} = buckling stress in transverse compression

Substitution of Eq.(24) into Eq.(23) yields the effective plate breadth and length as a function of membrane strain components.

$$\frac{b_e}{b}=\frac{1}{2}\left\{1+\frac{\sigma_{xcr}}{E\varepsilon_{xav}}\right\}$$
$$\frac{a_e}{a}=\frac{1}{2}\left\{1+\frac{\sigma_{ycr}}{E\varepsilon_{yav}}\right\} \qquad (25)$$

Also, substituting Eq.(25) into Eq.(22), the relationship between average axial stress and average axial strain of the collapsed unit is given

$$\sigma_{xav}=\frac{1}{2}\left\{1+\frac{\sigma_{xcr}}{E\varepsilon_{xav}}\right\}\sigma^{u}_{xmax}$$
$$\sigma_{yav}=\frac{1}{2}\left\{1+\frac{\sigma_{ycr}}{E\varepsilon_{yav}}\right\}\sigma^{u}_{ymax} \qquad (26)$$

The above equation is rewritten by the incremental form as :

$$\Delta\sigma_{xav}=-\frac{\sigma^{u}_{xmax}}{2}\frac{\sigma_{xcr}}{E\varepsilon^{2}_{xav}}\Delta\varepsilon_{xav}$$
$$\Delta\sigma_{yav}=-\frac{\sigma^{u}_{ymax}}{2}\frac{\sigma_{ycr}}{E\varepsilon^{2}_{yav}}\Delta\varepsilon_{yav} \qquad (27)$$

On the other hand, it is assumed that shearing modulus of the collapsed unit is nearly zero, that is,

$$\Delta\tau_{xyav}=0\cdot\Delta\gamma_{xyav}=0 \qquad (28)$$

Accordingly, the relationship between the average stress increment and the average strain increment will be obtained.

$$[D]=[D]^{U}_{pl} \qquad (29)$$

(ii) Idealized Stiffened Plate Unit

For the idealized stiffened plate unit, the post-collapse behavior is different according to the collapse mode

1) after local collapse

In this case, the stiffness of the unit is calculated by adding the collapsed plate part and the intact longitudinal /transverse stiffener as :

$$[D]=[D]^{U}_{sp}=[D]^{U}_{pl}+[D]^{EXY}_{st} \qquad (30)$$

2) after longitudinal panel collapse(longitudinal stiffeners collapsed)

In this case, the stiffness of the unit is calculated by adding the collapsed plate part, the intact transverse stiffener and the collapsed longitudinal stiffener as :

$$[D]=[D]^{U}_{sp}=[D]^{U}_{pl}+[D]^{EY}_{st}+[D]^{UX}_{st} \qquad (31)$$

where

$$[D]^{EY}_{st}=\begin{bmatrix}0&0&0\\0&En_{sy}A_{sy}/at&0\\0&0&0\end{bmatrix}$$

$[D]^{UX}_{st}$ = stress-strain matrix of the collapsed longitudinal stiffener which is the same with the idealized beam-column unit

3) after transverse panel collapse (transverse stiffeners collapsed)

In this case, the stiffness of the unit is calculated by adding the collapsed plate part, the intact longitudinal stiffener and the collapsed transverse stiffener as :

$$[D]=[D]^{U}_{sp}=[D]^{U}_{pl}+[D]^{EX}_{st}+[D]^{UY}_{st} \qquad (32)$$

where

$$[D]_{st}^{EXY} = \begin{bmatrix} En_{sx}A_{sx}/bt & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$[D]^{UY}_{st}$ = stress-strain matrix of the collapsed transverse stiffener which is the same with the idealized beam-column unit

4) after overall collapse

In this case, the stiffness of the unit is calculated by adding the collapsed plate part and the collapsed longitudinal/transverse stiffener as :

$$[D] = [D]_{sp}^{U} = [D]_{pl}^{U} + [D]_{st}^{U} \qquad (33)$$

where $[D]_{st}^{U}$ = stress-strain matrix of the collapsed longitudinal/transverse stiffener

(5) Segment OC : Linear Elastic Behavior

In this case, behavior of the unit is linear, and the [D] matrix is given as follows.

(i) Idealized Unstiffened Plate Unit

$$[D] = [D]_{pl}^{E} = \frac{E}{1-\nu^2}\begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & (1-\nu)/2 \end{bmatrix} \qquad (34)$$

(ii) Idealized Stiffened Plate Unit

The stiffness of the unit is calculated by adding the flat plate part and the intact longitudinal/transverse stiffener.

$$[D] = [D]_{sp}^{E} = [D]_{pl}^{E} + [D]^{EXY}_{st} \qquad (35)$$

(6) Criterion of Point C : Yield Strength

If the equivalent stress reaches the yield stress, the unit will be yielded. Here, for checking the yield strength, the following Mises' condition is employed.

$$f_y = \sigma_{xav}^2 - \sigma_{xav}\cdot\sigma_{yav} + \sigma_{yav}^2 + 3\tau_{xyav}^2 - \sigma_o^2 = 0 \qquad (36)$$

(7) Segment CD : Post-Yield Behavior

Because of the strain-hardening effect, the yielded unit can still carry further tensile loading. In the present method, therefore, the elasto-plastic stress-strain relationship taking into account the strain-hardening effect is derived as in the same manner with the conventional FEM. If unloading in the yielded unit occurs, the elastic stress-strain relation is employed.

(i) Idealized Unstiffened Plate Unit

$$[D] = [D]_{pl}^{p} = [D]_{pl}^{E} - \frac{[D]_{pl}^{E}\{\partial fy/\partial\sigma\}\{\partial fy/\partial\sigma\}^T[D]_{pl}^{E}}{E_p + \{\partial fy/\partial\sigma\}^T[D]_{pl}^{E}\{\partial fy/\partial\sigma\}} \qquad (37)$$

where E_p indicates the tangent modulus accounting for the strain-hardening effect and fy is the yield function in Eq.(36).

(ii) Idealized Stiffened Plate Unit

$$[D] = [D]_{sp}^{p} = [D]_{sp}^{E} - \frac{[D]_{sp}^{E}\{\partial fy/\partial\sigma\}\{\partial fy/\partial\sigma\}^T[D]_{sp}^{E}}{E_p + \{\partial fy/\partial\sigma\}^T[D]_{sp}^{E}\{\partial fy/\partial\sigma\}} \qquad (38)$$

(8) Criterion of Point D : Ultimate Tensile Strength

If the equivalent stress exceeds the ultimate tensile stress of the material, the unit will reach the ultimate tensile strength.

$$f_T = \sigma_{xav}^2 - \sigma_{xav}\cdot\sigma_{yav} + \sigma_{yav}^2 + 3\tau_{xyav}^2 - \sigma_T^2 = 0 \qquad (39)$$

(9) Segment DE : Post-Tensile Strength Behavior

As far as the tension-deformation is continued, the internal stress goes down in this range. As in the idealized beam-column unit, the tangent modulus can be quantified based on the tensile test result.

(i) Idealized Unstiffened Plate Unit

The basic relation between stress and strain is

$$\frac{\sigma_{xav} - \nu\sigma_{yav}}{\varepsilon_i} = \frac{\sigma_{yav} - \nu\sigma_{xav}}{\varepsilon_i} = \frac{\tau_{xyav}}{2(1+\nu)\,\gamma_{av}} = \frac{\sigma_i}{\varepsilon_i} \tag{40}$$

where σ_i, ε_i = equivalent stress and strain, respectively

It is assumed that the relation between the equivalent stress and the equivalent strain is linear in this range.

$$\frac{\sigma_i}{\varepsilon_i} = E_f \tag{41}$$

where E_f = tangent modulus in the post-tensile strength range

Accordingly, the stress-strain matrix reads

$$[D] = [D]^F_{pl} = \frac{E_f}{1-\nu^2}\begin{bmatrix} 1 & \nu_f & 0 \\ \nu_f & 1 & 0 \\ 0 & 0 & (1-\nu_f)/2 \end{bmatrix} \tag{42}$$

where ν_f denotes Poisson's ratio in the post-tensile strength range and for steel it may be taken as $\nu_f = 0.5$ because the material is in fully plastic regime.

(ii) Idealized Stiffened Plate Unit

$$[D] = [D]^F_{sp} = [D]^F_{pl} + [D]^{FXY}_{st} \tag{43}$$

where

$$[D]^{FXY}_{st} = \begin{bmatrix} E_f n_{sx} A_{sx}/bt & 0 & 0 \\ 0 & E_f n_{sy} A_{sy}/at & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

(10) Criterion of Point E : Ductile-Fracture Strength

As in the idealized beam-column unit, if the tensile strain of the unit exceeds the critical fracture strain, the ductile-fracture will occur.

$$\varepsilon_{eq} \geq \varepsilon_{fcr} \tag{44}$$

where ε_{eq} is the equivalent tensile strain in the unit and ε_{fcr} is the critical fracture strain which is obtained from the tensile test result. As mentioned, the effect of initial crack damage can also be included in the determination of the crtical fracture strain.

(11) Segment EF and FG : Post-Fracture Behavior

The fractured unit is not able to carry the tensile load further. In the subsequent loading step, therefore, the modulus of material is set to be zero, as in the idealized beam-column unit. In this case, the stress-strain matrix for both unstiffened and stiffened plate units becomes zero and also the accumulated membrane stress in the fractures unit sgould be released[20].

3. Analysis of the 1/3-Scale Frigate Test Model under Sagging Moment

Dow[4] carried out the progressive collapse test for the 1/3-scale hull model of a leander class frigate under sagging moment. The ISSC committee Ⅲ.1 is trying to analyze the progressive collapse behavior of this model. Many researchers are participated in this work and the same definitions for the geometry and the initial imperfections of the model are suggested[19].

3.1 Test Model

Dimension of the test model is 18m length, 4.1m beam and 2.8m depth. Fig. 6 shows midship section of the test model. The material properties of the structural members are defined by

$E = 207$ GPa(Young's modulus)
$\sigma_0 = 245$ MPa(yield stress)
$\nu = 0.3$(Poisson ratio)

Basically, the material is assumed to be linear elastic, perfectly plastic by the ISSC committee[19]. Also the present study aims to investigate the nonlinear behavior due to the excessive-tension deformation and for this purpose the following magnitudes which are selected from the typical tensile test results of steel material are assumed by

$E_p = 0.01$ E(tangent modulus after yielding)
$E_f = -E$(tangent modulus after ultimate tensile strength)
$\varepsilon_{fcr} = 0.15$(critical rupture strain)

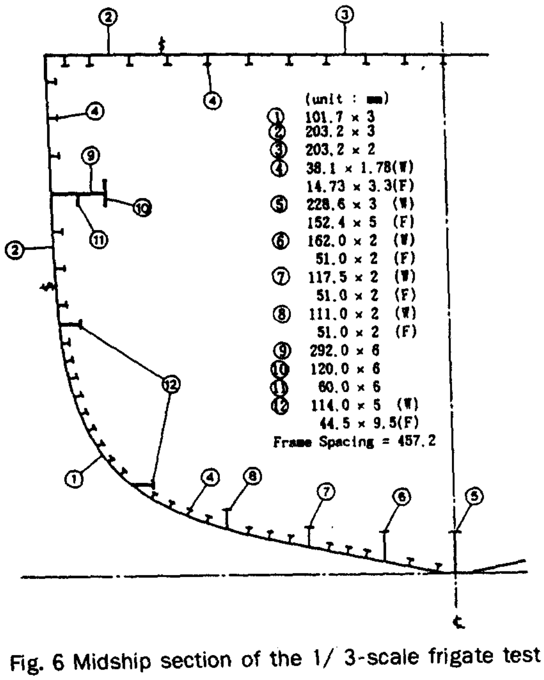

Fig. 6 Midship section of the 1/ 3-scale frigate test model

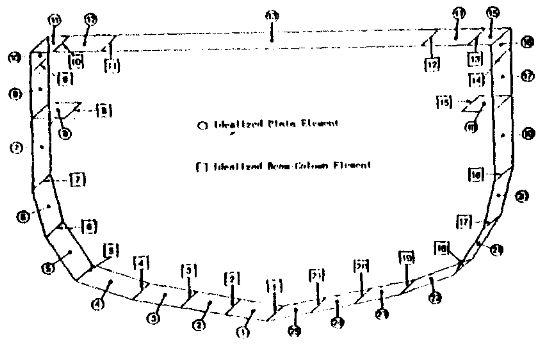

Fig. 7 ALPS/ ISUM modelling for the 1/ 3-scale fregate test model

The initial deflection of plates between stiffeners is suggested to be in the shape of one-half sine wave in both longitudinal and transverse direction with the maximum deflection at midpoint given by

$\delta / b = 0.030$ for deck plating
$\quad = 0.010$ for side shell plating

where δ = magnitude of initial deflection
$\quad b$ = breadth of plate between stiffeners

The residual stress in the plate between stiffeners is suggested to have the well-known square shape which forms a self-equilibrium pattern(see Fig. 8 of reference[19]). The magnitude of the residual stress in the two outer zones is equal to the tension yield stress while the residual stress magnitude of the middle zone in the longi-

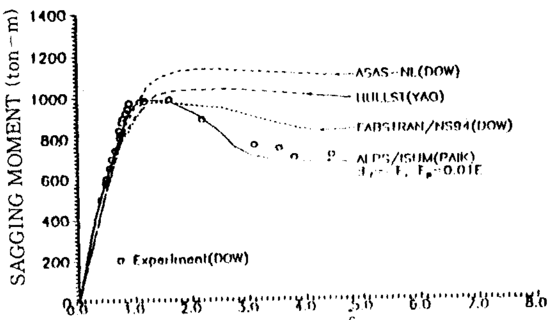

Fig. 8 The sagging moment-curvature response for the 1/ 3-scale frigate test model

tudinal direction is compressive, given by Table 3 of reference 4, namely

$$\sigma_{rx} = -125 \text{ MPa for 2mm plate}$$
$$= -147 \text{ MPa for 3mm plate}$$

where σ_{rx} = magnitude of the residual stress in the longitudinal direction

By the way, since the welding is performed along the transverse as well as the longitudinal edge of plate panels, the transverse residual stress which also affects the stiffness and strength of the structure will exist. According to the measured data for center panels, the residual stress in the transverse direction is about 19% of the longitudinal one. In this regard, the compressive residual stress magnitude in the transverse direction can be assumed by

$$\sigma_{ry} = 0.19\,\sigma_{rx} = -23.75 \text{ MPa for 2mm plate}$$
$$= -27.93 \text{ MPa for 3mm plate}$$

where σ_{ry} = magnitude of the residual stress in the transverse direction

3.2 Discussion of Results

The computer program ALPS/ISUM[21] has been developed based on the present theory. Procedure for the progressive collapse analysis of plated structures such as ships is found in the previous papers[17],[18] When a ship's hull is under bending moment, the position of neutral axis changes and the computer program also takes into account this effect automatically.

Fig. 7 shows the ALPS/ISUM model for the test model. Midship part in one frame spacing is taken as extent of the modelling and a full-hull is modelled. All the three kinds of the idealized structural elements, described in this paper are used for this modelling. Here, the "hard element" is introduced, in which buckling does not occur but yielding will take place. In this analysis, plate parts at the deck-side corner, 2nd deck girder, 3rd deck, 4th deck, center girder and side girder which are rigidly connected with transverse frames are considered as the "hard element".

As sagging moment increases, the idealized structural units will show various failure modes, defined in Table 1. Symmetric boundary condition at the center line of bottom part and restriction of rigid-body motion are prescribed. The bending curvature for the hull is applied incrementally.

Fig. 8 compares the sagging moment-curvature curve for the test model between the Dow's experimental result and the ALPS/ISUM solution. The existing numerical results obtained by using other computer programs such as the Dow's FABSTRAN/NS94[4], the Dow's ASAS-NL[4], the Yao's HULLST[10] are also compared. Here, both FABSTRAN/NS94 and HULLST are based on the Smith's method[9] but the ASAS-NL code is applying the nonlinear finite-element method. The solution by ALPS/ISUM is coincided with the experimental result.

Fig. 9, 10 and Table 2 indicate solutions by ALPS/ISUM assuming Ep = 0.01E and Ef = −E. Fig. 9 shows the average stress-displacement curve for typical members under com-

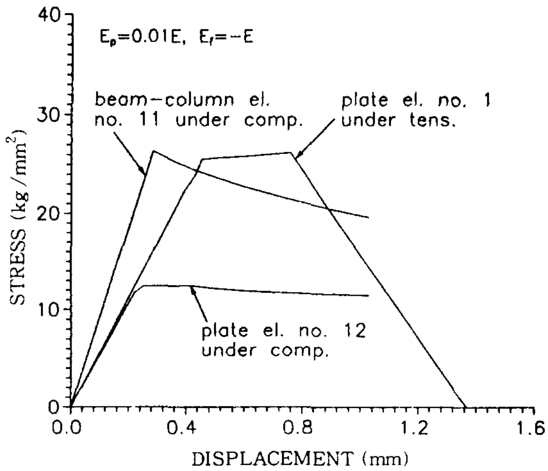

Fig. 9 The axial stress-displacement curve of typical compressed and tensiled members for the 1/3-scale frigate test model

Table 2 Failure history for the 1/ 3-scale frigate test model

Applied Sagging Moment (ton-m)	Plate		Beam-Columm	
	Element No.	Failure mode	Element No.	Failure Mode
486.67			11, 12	1
6002.29	13	2		
640.46	12, 14	2		
800.12	9, 17	2		
898.95	1, 2 24, 25	5		
946.47	8, 18	2		
953.39	3, 23	5		
976.20	4, 22	5		
987.38	7, 19	2		
※ 987.75	1, 2 24, 25	6		
962.49	3, 23	6		
915.63	4, 22	6		
896.25	5, 21	5		

※ Ultimate collapse strength

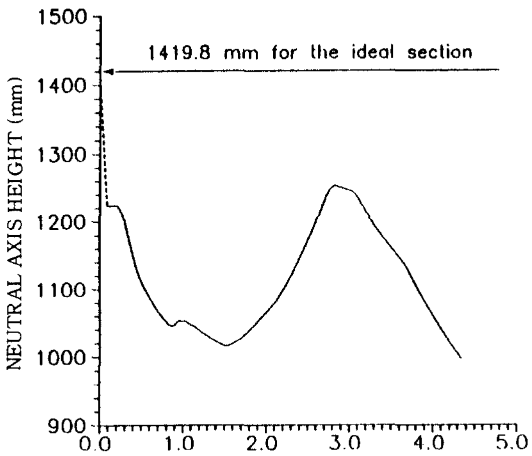

Fig. 10 The change of the neutral axis position with increase in the sagging moment for the 1/ 3-scale frigate test model

pression or tension. The computed moment of inertia for the unreduced, ideal midship section was $6.237 \times 10^{10} mm^4$.

Fig. 10 represents change of the horizontal neutral axis height. The computed position of the neutral axis above the base line for the unreduced, ideal midship section was 1419.8mm but since the actual members have the initial imperfections the real position of the neutral aixs is different from the ideal one. The computed position of the neutral axis for the real midship section was 1223mm.

Furthermore, if the failure of structural members occurs with increase in the applied load, the position of the neutral axis changes. At first it moves to downward due to collapse of deck structure, and then it moves to upward due to yielding of bottom structure. The failured region will be expanded to mid-height part of the section. In the present modelling, the bottom girders are considered to be hard, the neutral axis position slightly moves to downward again. Table 2 indicates failure history of the test model with increase in the applied sagging moment. In this analysis, the critical fracture strain of the material is assumed to be 15%, but for this model the ductile-fracture(failure mode number = 7) did not occur.

Fig. 11 investigates the effect of the post-tensile strength behavior on the progressive collapse behavior of the whole structure. Parametric analysis is performed varying the magnitude of Ef. It is observed that the progressive collapse behavior is the same each other up to the ultimate collapse strength but in the post-collapse range the behavior is different by the value of Ef.

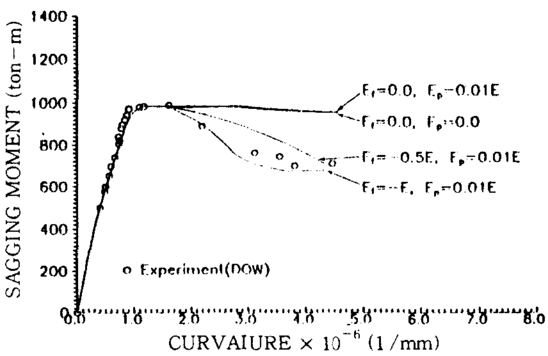

Fig. 11 Influence of the excessive tension-deformation on the progressive collapse behavior for the 1/ 3-scale frigate test model

As the absolute value of Ef increases, the gradient of "unloading path" becomes larger. The solution obtained assuming Ep = 0.01E and Ef = −0.5E is very similar with the Dow's FABSTRAN/NS94 result.

From the above observation, it is obvious that the excessive tension-deformation of individual members after the ultimate tensile strength is also a significant factor affecting the progressive collapse behavior of the whole structure, particularly in the post-ultimate collapse range.

4. Concluding Remarks

The importance of excessive tension-deformation effect after yielding has been disregarded in the existing idealized structural units although the ductile-collapse behavior due to axial compression and shearing force is treated carefully. In this paper, the existing idealized structural units are improved so as to include the excessive tension-deformation effect. For this purpose, a simplified mechanical model for the stress-strain relation of steel members under tensile load is suggested. Through the collapse analysis of a large size test hull model, the role of the excessive tension-deformation of local members on the overall collapse behavior is demonstrated.

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