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Dynamic material properties of marine steels under impact loadings

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ABSTRACT

Steel is the major material for ships and offshore structures which are prone to be subjected to impact loadings. Therefore, the correct understandings of the dynamic material properties of marine structural steels are necessary for the proper predictions and evaluations of the performances of marine structures under impacts. This paper presents empirical equations with which flow stresses can be defined considering strain and strain rate hardening effects. The equations were derived using mill certificates and static and dynamic tensile test results. The newly derived equation were utilized for unstiffened plates subjected to lateral mass impacts and their responses were compared with those using existing equations.

INTRODUCTION

The responses of structures under impact loadings can be divided into elasto-plastic deformation stage, elastic spring-back stage and elastic vibration stage. During the elasto-plastic stage marine steels may show strain hardening and strain rate hardening. When the applied impact is severe fracture may occur in the impacted structures. The problems are how to appropriately consider the stain and strain rate hardenings and how to construct the acceptable fracture criterion for marine steels.

The static material properties of marine steels are quite well known. However, the dynamic material properties are not fully understood and those are loosely assumed in the dynamic response analyses especially for impact loadings.

In this study a number of static tensile tests were performed on various grades of steels and a huge number of mill certificates are collected and analyzed. Using the available material data and adopting the Ludwick formula in a modified form a new constitutive equation was developed considering the yield plateau and strain hardening. The dynamic tensile tests on SS41, AH36 and HSLA steels were also performed and analyzed. Based upon the dynamic tensile tests results a dynamic constitutive equation was obtained employing the Cowper–Symonds equation for the dynamic magnification factor on yield strength.

Collision tests on unstiffened plates were conducted causing plastic damages. Dynamic fracture tests were also performed on unstiffened plates using a collision testing machine. The availability of the newly obtained dynamic constitutive equation has been substantiated using the collision test results. A new fracture criterion is also developed using the dynamic fracture test results.

STATIC CONSTITUTIVE EQUATION

When marine structures are subjected to impact loadings like slamming the material undergoes large strain. Therefore, the constitutive relations covering large strain are necessary for the analysis. In Figure 1 a static constitutive relationship is provided obtained from the static tensile test on a higher strength steel for marine use. As can be seen in the figure after reaching the yield strength (σ_Y) of the material a yield plateau is apparent and followed by strain hardening. After reaching the ultimate tensile strength (σ_T) of the material the so-called necking occurs and the cross-section area decreases.

The constitutive relation shown in Figure 1 can be approximated as that shown in Figure 2, which is represented by yield point (σ_Y, ε_Y), hardening start point (σ_Y, ε_{HS}), and ultimate point (σ_T, ε_T). Therefore, the remaining task is to define the hardening start strain (ε_{HS}) ultimate tensile strength (σ_T) and ultimate tensile strain (ε_T) for various steels.

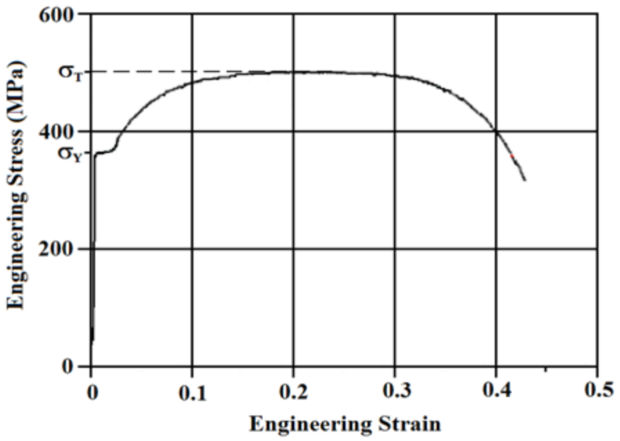

Figure 1 Constitutive relationship of steel for marine use

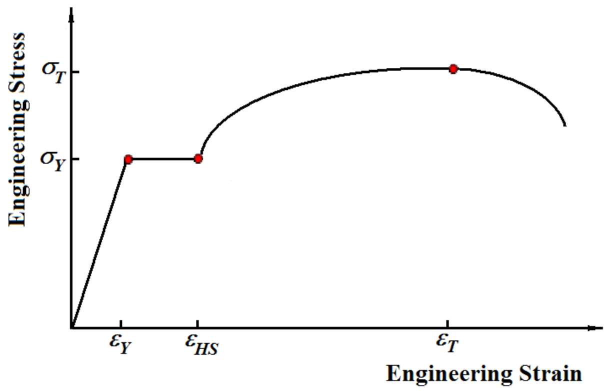

Figure 3 Simplified constitutive relationship of steel for marine use

Yield strength and ultimate tensile strength

In Table 1, the means and COVs of the yield strengths and ultimate strengths of various steels for marine use are summarized. As can be seen in the table, the mean values of yield strengths of all grades are much higher than those specified as minimum in Classification Societies' Rules. However, the means of ultimate strengths of all grades are in the ranges of their specifications.

Table 1 Mechanical properties of various steels for marine use

Material	No. of specimens	Yield strength (σ_Y)		Ultimate tensile strength (σ_T)		σ_T/σ_Y
		mean (MPa)	COV	Mean (MPa)	COV	
A	2323	312	0.085	451	0.036	1.443
B	22	315	0.057	448	0.017	1.425
D	46	315	0.071	451	0.039	1.432
E	3	316	0.144	452	0.034	1.432
AH32	2602(5)*	386	0.088	514	0.034	1.332
DH32	83(7)	375	0.049	506	0.036	1.349
AH36	2101(5)	433	0.076	547	0.043	1.263
DH36	322(45)	427	0.060	542	0.035	1.269
EH36	41(19)	432	0.046	523	0.033	1.211
LT-steel	20(20)	363	0.028	472	0.022	1.298
HSLA	2(2)	827	0.007	849	0.004	1.027

note: * the number in parentheses is of those obtained from in-house tensile test data.

Simple expression, Eq. (1), is derived to predict the ultimate strength with the provided yield strength by regression analysis.

$$\frac{\sigma_T}{\sigma_Y} = \left\{1.592 + 0.431 \times \ln\left(\frac{E}{1000\sigma_Y}\right)\right\} \tag{1}$$

where *E* is the Young's modulus and assumed to be 206000 (N/mm^2).

Ultimate strain and hardening start strain

Using the in-house tensile test data the equations for ultimate tensile strain (ε_T), Eq. (2) and hadening start strain (ε_{HS}), Eq. (3), were obtained by regression analysis.

$$\frac{\varepsilon_T}{\varepsilon_Y} = exp\left\{-11.57\left(\frac{E}{1000\sigma_Y}\right)^2 + 15.13\left(\frac{E}{1000\sigma_Y}\right) - 0.191\right\} \tag{2}$$

$$\frac{\varepsilon_{HS}}{\varepsilon_Y} = exp\left\{0.762\left(\frac{\varepsilon_T}{\varepsilon_Y}\right)^{0.254}\right\} \tag{3}$$

Static constitutive equation

The constitutive equation considering the yield plateau can be expressed as follows:

$$\sigma_{tr} = E\varepsilon_{tr} \qquad \text{when } 0 < \varepsilon_{tr} \le \varepsilon_{Y,tr} \tag{4a}$$

$$\sigma_{tr} = \sigma_{Y,tr} + (\sigma_{HS,tr} - \sigma_{Y,tr})\frac{\varepsilon_{tr}-\varepsilon_{Y,tr}}{\varepsilon_{HS,tr}-\varepsilon_{Y,tr}} \qquad \text{when } \varepsilon_{Y,tr} < \varepsilon_{tr} \le \varepsilon_{HS,tr} \tag{4b}$$

$$\sigma_{tr} = \sigma_{HS,tr} + K(\varepsilon_{tr} - \varepsilon_{HS,tr})^n \qquad \text{when } \varepsilon_{HS,tr} < \varepsilon_{tr} \tag{4c}$$

where

$$n = \frac{\sigma_{T,tr}}{\sigma_{T,tr}-\sigma_{HS,tr}}(\varepsilon_{T,tr} - \varepsilon_{HS,tr}), \tag{5}$$

$$K = \frac{\sigma_{T,tr}-\sigma_{HS,tr}}{(\varepsilon_{T,tr}-\varepsilon_{HS,tr})^n} \tag{6}$$

Therefore, when yield strength, ultimate tensile strength, hardening start strain and ultimate tensile strain are provided the constitutive equation can be constructed using eqns (4a-c) together with eqns (5) and (6) considering not only the strain hardening but also the yield plateau.

DYNAMIC CONSTITUTIVE EQUATION

It is well known that when the strain rate becomes larger the strength is increasing for structural steels. Before entering the yield plateau there is a yield delay and followed by a yield plateau whose width becomes wider when the strain rate is increasing. The strain hardening effect becomes smaller for higher strain rates.

When neglecting the initial yield delay the constitutive relation can be expressed just like what did for static case using yield point, hardening start point and ultimate point. Dynamic tensile tests are necessary to obtain the information regarding the strain rate effects on the constitutive relations.

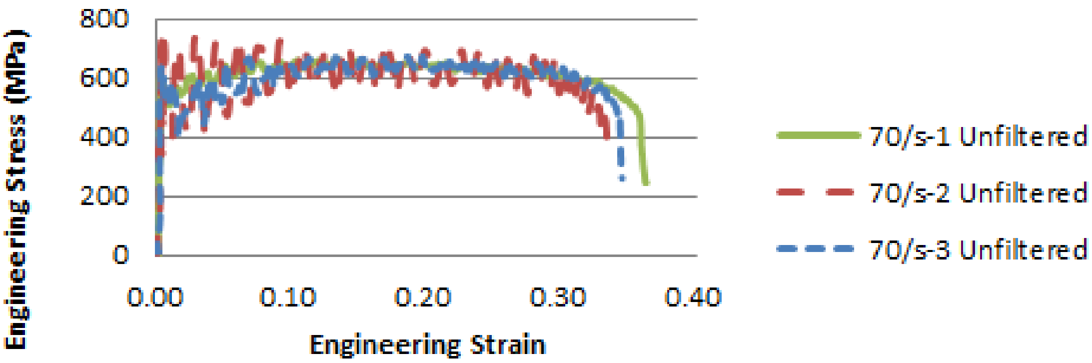

Figure 4 Raw data obtained from dynamic tensile tests

Dynamic tensile test

In this study Instron VHS-65/80-25 was used for dynamic tensile tests, which is of Korean Institute of Material Science located in Chanwon, Korea. For dynamic tensile test a different coupon from the static test needs to be used and three kinds of material were tested including SS41, AH36 and HSLA steels.

The dynamic tensile test results of AH36 are shown in Figure 4, where the strain rate is 70/s. The raw data are difficult to use and those need to be filtered. The data for other materials are similar to those of AH36 in general. However, HSLA steel seems insensitive to strain rate.

Equations for dynamic constitutive relation

Using the dynamic tensile test data the equations for dynamic yield strength, dynamic ultimate tensile strength, dynamic hardening start strain and dynamic ultimate tensile strain have been derived. The derived equations are as follows:

Dynamic yield strength: The final equation to determine the dynamic yield strength can expressed as Eq. (7).

$$\frac{\sigma_{YD}}{\sigma_Y} = 1 + \left\{ \left(\frac{E\sigma_T}{1000\sigma_Y^2} \right)^{4.89} \left(\frac{\dot{\varepsilon}}{233.6} \right) \right\}^{0.333} \quad (7)$$

Dynamic ultimate tensile strength: The equation for dynamic ultimate tensile strength is expressed as Eq. (8).

$$\boldsymbol{\frac{\sigma_{TD}}{\sigma_{YD}} = 1 + 0.12\dot{\varepsilon}^{\left(-\frac{1}{a}\right)}} \quad (8)$$

where

$$\boldsymbol{a = 11.14 \times exp\left(\frac{1.38\sigma_Y}{\sigma_T}\right)}$$

Dynamic hardening start strain: The equation for dynamic hardening start strain has been derived as eqn (9).

$$\boldsymbol{\frac{\varepsilon_{HSD}}{\varepsilon_{HS}} = 1 + (b\dot{\varepsilon})^{0.3}} \quad (9)$$

where

$$b = 10.2exp\left\{-0.52\left(\frac{1000\sigma_Y}{E}\right)^{2.2}\left(\frac{\sigma_T}{\sigma_Y}\right)^{2.8}\right\}$$

Dynamic ultimate tensile strain: The equation for dynamic ultimate tensile strain has been derived as Eq. (10).

$$\frac{\varepsilon_{TD}}{\varepsilon_T} = (\mathbf{1} + \frac{\dot{\varepsilon}}{c})^{-0.333} \tag{10}$$

where

$$c = 4.71\left\{(\frac{1000\sigma_Y}{E})^8(\frac{\sigma_T}{\sigma_Y})^{0.3}\right\}^{2.08}$$

Using the equations for dynamic yield strength, dynamic ultimate strength, dynamic hardening start strain and dynamic ultimate tensile strain, Eqs. (7) ~ (10), the dynamic constitutive relation can be constructed considering the strain hardening and strain rate hardening.

SUBSTANTIATION OF NEW EQUATION

Plastic deformation

In order to substantiate the availability of the newly derived dynamic constitutive relationship, plastic deflection test results were utilized. The comparison results are provide in Table 2 where the predictions by using the newly derived equations are compared with those obtained by using Cowper-Symonds equation together with the static tensile test results.

Table 2 Numerical predictions of permanent deflections using different constitutive equations

model	non-dimensional permanent deflection			ratio	
	exp.	New*	CS**	New/exp.	CS/exp.
SE-5-1	7.25	7.62	7.95	1.05	1.10
SE-4-1	7.05	7.43	7.74	1.05	1.10
SE-3-1	6.69	7.09	7.63	1.06	1.14
SE-5-2	9.55	9.59	9.89	1.00	1.04
SE-4-2	8.35	9.23	9.54	1.10	1.14
SE-3-2	8.02	8.99	9.11	1.12	1.14
SE-5-3	9.90	10.28	10.61	1.04	1.07
SE-4-3	11.65	9.77	10.13	0.84	0.87
SE-3-3	8.39	9.27	9.70	1.10	1.16
			Average	1.04	1.08
			COV (%)	8.12	8.23

Note:
* New is the prediction obtained by using the newly derived equation.
** CS is the prediction obtained using Cowper-Symonds equation together with the static tensile test results.

Fracture criterion

A fracture criterion was derived using the newly derived equation and dynamic fracture test results. Using the results of the eight collision tests on plates generating perforation the rupture strains for the shear fracture criterion were obtained. The obtained rupture strain was utilized in the further numerical analyses in this study. It is well known that the rupture strain is very dependent on the mesh size in finite element analysis. Changing the ratios of mesh size to plate thickness numerical computations were performed. Samuelides et al.(2007) proposed Eq. (11). Following the same parameter a new equation for fracture criterion has been developed as Eq. (12)

$$\varepsilon_f = 0.056 + 0.54\frac{h}{l_e} \tag{11}$$

$$\varepsilon_f = 0.1 + 0.26\frac{h}{l_e} \tag{12}$$

Table 3 Selected shear strain fracture criterion

model	Shear strain fracture criterion	
	New	CS
F-3-1	0.31	0.19
F-3-2	0.31	0.18
F-4-1	0.37	0.23
F-4-2	0.36	0.21
F-4-3	0.36	0.21
F-5-1	0.28	0.18
F-5-2	0.33	0.18
F-5-3	0.37	0.23

CONCLUSIONS

In this study, utilizing the mill certificates and static tensile test results together with dynamic tensile test results, a new dynamic constitutive equation is developed. The availability of the newly derived equation is substantiated with lateral collision test data. The new equation provides slightly better results when comparing with Cowper-Symonds equation. A new fracture criterion is also developed as Eq. (12). It is necessary to perform more dynamic tensile tests on different materials and more dynamic fracture tests were required.

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