Reliability-Based Design of Doubler Plates for Ship Structures

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Abstract

Maintenance, inspection, and repair are key aspects of managing the structural integrity of ship systems in a life cycle framework. For example, an inspection program can be developed with the objective of maintaining the structural integrity of a ship. It can start with system definition, followed by qualitative reliability assessment, and then quantitative reliability assessment with the objective of performing reliability-based design for maintaining system integrity. Doubler plates currently offer a temporary solution for plate damage in ship structures. The temporary nature of this fix stems from the lack of data on their performance and an engineering design guidance. In this study, a reliability-based design model for an unstiffened panel with doubler plate(s) was developed using both finite difference (FD) and finite element (FE) procedures. Partial safety factors were also determined to account for the uncertainties in strength and load effect. The First-Order Reliability Method (FORM) was used to develop the partial safety factors.

1. Introduction

Doubler plates currently offer a temporary solution for plate damage in ship structures. The temporary nature of this fix stems from the lack of data on their performance and an engineering design guidance [3]. There is a need to survey the use of doubler plates, document experiences with their use, and develop guidance on their design and uses with any associated limitations. This study will survey such experiences, and develop the needed guidance.

Repair actions can be classified into two categories: (1) temporary, and (2) permanent. The use of doubler plates, or lapped plating, has become extensive, and is an inexpensive method of repairing corroded plating, cracked plates, or defective welds. A doubler plate is nothing but a plate that is added to top of the defective area and welded around the plate's perimeter (see Figure 1). While this method of repair has economic advantages, it falls in the temporary repair category and its use has never been accepted as a permanent repair. This temporary repair method would maintain structural integrity until the ship is either in dry-dock or in restricted availability, and is followed by permanent repairs made to the original corroded structure. In the maintenance of commercial ships the use of doublers for anything other than temporary repair is currently not recommended. The objections to their use are both on technical and operational grounds.

Hull girder structural components of a ship are basically rolled shapes or built-up sections that are composed of plate elements (flat plates). The strength of these structural components is usually governed by local buckling of these plate elements or flat plates that make up the cross-section. Such local buckling means that the buckled element will no longer take its proportionate share of any additional load the column is to carry. This also means that efficiency of the cross section is reduced. This situation resembles the case where there is a crack or a hole in one of the plate elements of stiffened panels of a ship, which needs an immediate remedy such as adding a welded doubler plate on top of the crack or the hole (see Figure 1b).

There are numerous factors that can affect the capacity (or strength) of flat plate with doublers plate. Among these factors are [3]:

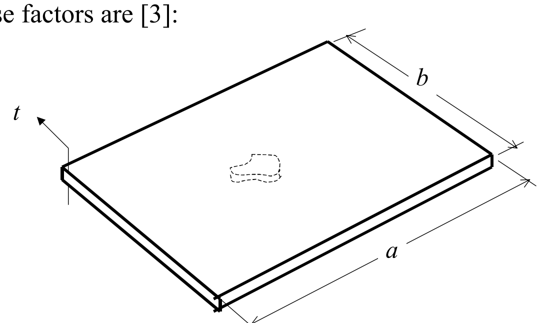

Figure 1a. Base plate

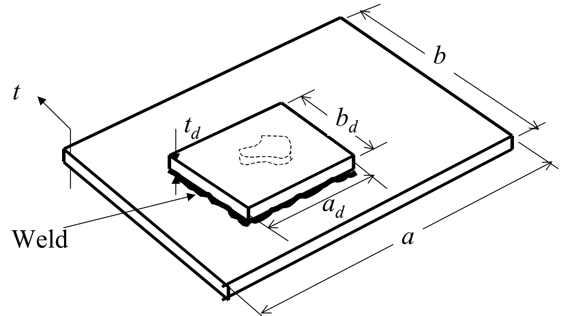

Figure 1b. Unstiffened panel with doubler plate

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1. The type of material that both the base structure and the doublers are made of,
2. The location of the doubler plate within the base structure,
3. The end conditions of the base plate,
4. The degree of corrosion and cracking on base plate, and
5. The type of welding along the perimeter of the doubler plate.

2. Reliability-based Design Methods

The reliability-based design of ship structures requires the consideration of the following three components: (1) loads, (2) structural strength, and (3) methods of reliability analysis. These three components are essential for the development of LRFD-based reliability design for ship hull girders. There are two primary approaches for reliability-based design [4]: (1) direct reliability-based design and (2) load and resistance factor design, LRFD. The direct reliability-based de-sign approach can include both Level 2 and/or Level 3 reliability methods. Level 2 reliability methods are based on the moments (mean and variance) of random variables and sometimes with a linear approximation of nonlinear limit states, whereas, Level 3 reliability methods use the complete probabilistic characteristics of the random variables [4]. In some cases, Level 3 reliability analysis is not possible because of lack of complete information on the full probabilistic characteristics of the random variables. Also, computational difficulty in Level 3 methods sometimes discourages their uses. The LRFD approach is called a Level 1 reliability method. Level 1 reliability methods utilize partial safety factors (PSF) that are reliability based; but the methods do not require explicit use of the probabilistic description of the variables.

2.1. Direct Reliability-based Design

The direct reliability-based design method uses all available information about the basic variables (including correlation) and does not simplify the limit state in any manner. It requires performing spectral analysis and extreme analysis of the loads. In addition, linear or nonlinear structural analysis can be used to develop a stress frequency distribution. Then, stochastic load combinations can be performed. Linear or nonlinear structural analysis can then be used to obtain deformation and stress values. Serviceability and strength failure modes need to be considered at different levels of the ship, i.e., hull girder, grillage, panel, plate and detail. The appropriate loads, strength variables, and failure definitions need to be selected for each failure mode. Using reliability assessment methods such as FORM, reliability indices β's for all modes at all levels need to be computed and compared with target reliability indices β's. The relationship between the reliability index β and the probability of failure is given by [1,2]

$$P_f = 1 - \Phi(\beta) \quad (1)$$

where Φ(.) = cumulative probability distribution function of the standard normal distribution, and β = reliability (safety) index. It is to be noted that Eq. 1 assumes all the random variables in the limit state equation to have normal probability distribution and the performance function is linear. However, in practice, it is common to deal with nonlinear performance functions with a relatively small level of linearity. If this is the case, then the error in estimating the probability of failure P_f is very small, and thus for all practical purposes, Eq. 1 can be used to evaluate P_f with sufficient accuracy [2].

2.2. Load and Resistance Factor Design

The second approach (LRFD) of reliability-based design consists of the requirement that a factored (reduced) strength of a structural component is larger than a linear combination of factored (magnified) load effects as given by the following general format [5]:

$$\phi R_n \geq \sum_{i=1}^{m} \gamma_i L_{ni} \quad (2)$$

where ϕ = strength factor, R_n = nominal (or design) strength, γ_i = load factor for the i^{th} load component out of m components, and L_i = nominal (or design) value for the i^{th} load component out of m components. In this approach, load effects are increased, and strength is reduced, by multiplying the corresponding characteristic (nominal) values with factors, which are called strength (resistance) and load factors, respectively, or partial safety factors (PSF's). The characteristic value of some quantity is the value that is used in current design practice, and it is usually equal to a certain percentile of the probability distribution of that quantity. The load and strength factors are different for each type of load and strength. Generally, the higher the uncertainty associated with a load, the higher the corresponding load factor; and the higher the uncertainty associated with strength, the lower the corresponding strength factor. These factors are determined probabilistically so that they correspond to a prescribed level of reliability or safety. It is also common to consider two classes of performance function that correspond to strength and serviceability requirements. The difference between the allowable stress design (ASD) and the LRFD format is that the latter use different safety factors for each type of load and strength. This allows for taking into consideration uncertainties in load and strength, and to scale their characteristic values accordingly in the design equation. ASD (or called working stress) formats cannot do that because they use only one safety factor as seen by the following general design format:

$$\frac{R}{FS} \geq \sum_{i=1}^{m} L_i \tag{3}$$

where R = strength or resistance, L_i = load effect, and FS = factor of safety. In this design format, all loads are assumed to have average variability. The entire variability of the strength and the loads is placed on the strength side of the equation. The factor of safety FS accounts for this entire variability.

In the LRFD design format, ship designers can use the load and resistance factors in limit-state equations to account for uncertainties that might not be considered properly by deterministic methods (i,e., ADS) without explicitly performing probabilistic analysis. The LRFD format as described herein is concerned mainly with the structural design of ship hull girders under combinations of different load effects. The intention herein is to provide naval architects and ship designers with reliability-based methods for their use in both early and final design stages and for checking the adequacy of the scantlings of all structural members contributing to the longitudinal and transverse strength of ships. The general form of the LRFD format that is used in this paper is given by Eq. 2. The probabilistic characteristics and nominal values for the strength and load components were determined based on statistical analysis, recommended values from other specifications, and by professional judgment. The LRFD general design formats for ship hull structural components are given by one of the following two main cases, limit sate 1, and limit sate 2, respectively:

$$\phi R_n \geq \gamma_s L_s + k_{WD}\gamma_{WD} L_{WD} \tag{4}$$

$$\phi R_n \geq \gamma_s L_s + k_w\left(\gamma_W L_W + k_D \gamma_D L_D\right) \tag{5}$$

where ϕ = strength factor, R_n = nominal (or design) strength such as the ultimate stress, γ_s = load factor for stillwater load effect such as bending moment, L_s = nominal (or design) value for stillwater load effect such as bending moment, k_{WL} = combined wave-induced and dynamic bending moment factor, and γ_{WD} = load factor for combined wave-induced and dynamic bending moment, L_{WL}= nominal (or design) value for wave-induced and dynamic bending moments effect, k_W = load combination factor, γ_W = load factor for waves bending moment load effect, L_W = nominal (or design) value for waves bending moment load effect, k_D = load combination factor, γ_D = load factor for dynamic load effect such as bending moment, and L_D = nominal (or design) value for dynamic load effect such as bending moment. The strength and load factors are called collectively partial safety factors (PSF's). These factors are determined using structural reliability methods based on the probabilistic characteristics of basic random variables for materials, geometry and loads including statistical and modeling (or prediction) uncertainties. The factors are determined to meet target reliability levels that were selected based on assessing previous designs. This process of developing LRFD rules to meet target reliability levels that are implicit in current practices is called code calibration.

2.3. Reliability Checking

The LRFD methods also provide formats for reliability (safety) checking for various types of hull structural elements [4]. In order to perform a reliability checking on these elements, the computed reliability safety index β resulting from reliability assessment using for example FORM should not be less than the target safety index β_0 as given by the following expression:

$$\beta \geq \beta_0 \tag{6}$$

Reliability checking for different classes of ship structural elements can also be performed using the general form of the load and resistance factor design format of Eq. 2. Depending on the limit state, the nominal strength R_n of the structural component shall meet one of following two main requirements for limit states 1 and 2, respectively:

$$R_n \geq \frac{\gamma_s L_s + k_{WD}\gamma_{WD} L_{WD}}{\phi} \tag{7}$$

$$R_n \geq \frac{\gamma_s L_s + k_W\left(\gamma_W L_W + k_D \gamma_D L_D\right)}{\phi} \tag{8}$$

3. Methodology for Developing Simplified Strength Models for Structural Members with Doubler Plates

Evaluation and assessment of doubler plates as well as the base structural components that are strengthened by these plates can be a very difficult task. In most cases the finite element analysis is the proper approach. However, sometimes a designer or an investigator might need a handy and quick tool to design and check out the adequacy of a weak structural element (e.g, unstiffened panel) that must be strengthened by a doubler plate. For this reason, simplified strength models are needed. The purpose of this paper is to review and assess the strength of various structural elements such as thin columns and flat unstiffened plates with doublers in order to develop simplified empirical formulas that can be used to assess and evaluate doublers structural elements. These simple models can be developed based on the results of both the finite-element and finite difference methods, and

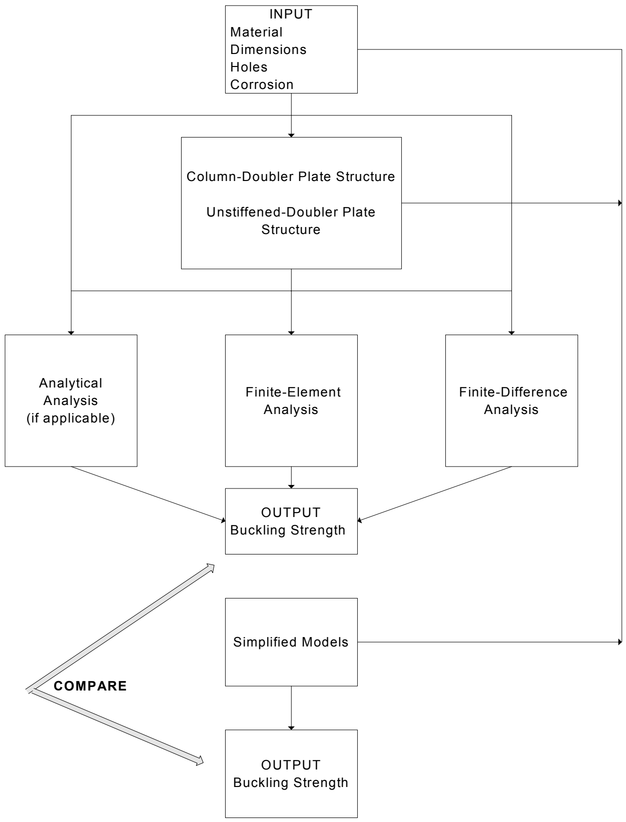

Figure 2. Methodology for developing simplified strength models for plates with doublers [3]

sometimes on analytical solutions. Figure 2 shows a schematic illustration of the general methodology for developing these simplified models for column and unstiffened plate element with doublers [3]

3.1. Column Buckling

Buckling is a mode of failure usually results from structural instability due compressive action on the structural member or element involved. The distinctive feature of buckling is the sudden catastrophic nature of the failure. The collapse of a column or a panel of a ship can lead to the collapse of the whole ship's hull girder. Although plates, shells, tubes, and various kinds of structural members have a tendency to buckle under different types of loadings, in this paper only straight members that are axially loaded and have constant cross sectional area will be considered.

The basic equation that governs column instability was developed by Euler in 1744. This equation is a relationship between the applied axial compression load P and the elastic restoring ability of the column as shown in Figure 3. If P is sufficiently small, the column will tend to remain straight and stable; whereas if P is too large, the column will be unable to maintain its straight position and will tend to become unstable and eventually buckle. Therefore, the value of P that will serve to distinguish the stable from the unstable conditions is desired.

The differential equation that governs column buckling is given by Euler (1744) as

$$\frac{d^2 y}{dx^2} = \frac{M}{EI} = -\frac{P}{EI} y \tag{9}$$

where P = applied compressive force, E = modulus of elasticity (Young's modulus) of the material, and I = moment of inertia of the cross section about the weak axis.

The exact solution for for Eq. 9 according to Euler (1744) is

$$P_{cr} = \frac{\pi^2 EI}{L^2} \tag{10}$$

The procedures for developing strength models start with a simple case such as a thin column structure; with doubler plate of known dimensions and material properties placed at different locations along the length of the column. A Finite-difference or finite-element analysis can then be performed to evaluate and assess the buckling strength of the column-doubler plate structure as the plate is placed at different locations along the length of the column. This analysis should be repeated for various dimensions of the doubler plate to insure that a reasonable range of input data will produce sufficient output results for developing a simple semi-analytical model. The procedure should also be repeated for a column with various degrees of damage (i.e., holes, corrosion, etc.) at which the doubler plate is placed. Based on the results of the finite-difference or finite-element analysis as well as on some analytical procedures, a simple formulation can be developed for predicting the buckling strength of the column-doubler plate structure. Once this simple formulation is developed, it should be verified using the same dimensions and material properties for both the column and the doubler plate.

3.2. Buckling of Uniaxially Compressed Unstiffened Plate

The differential equation that governs plate buckling was developed by Timoshenko (1961) and modified by Gerstle (1967) as (see Figure 4)

$$\frac{\partial^4 w}{\partial x^4} + 2\frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} = -\frac{N_x}{D}\frac{\partial^2 w}{\partial x^2} \tag{11}$$

where $N_x = \sigma_{cr}\, t$ and D = plate rigidity and is given by

$$D = \frac{Et^3}{12\left(1-\nu^2\right)} \tag{12}$$

The elastic buckling unit stress can be expressed as

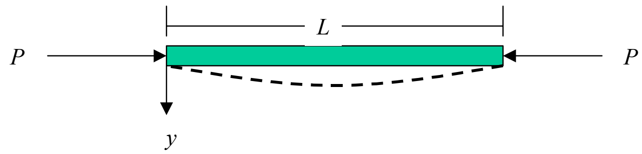

Figure 3. Euler column

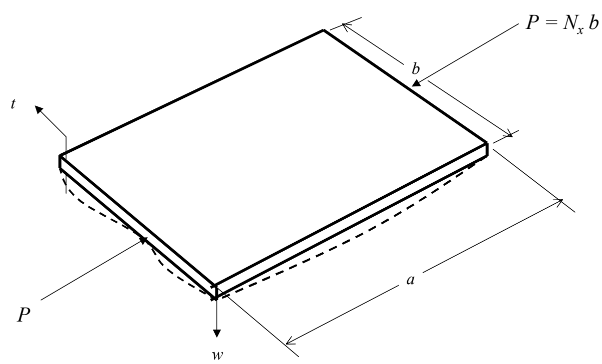

Figure 4. Plate Under uniaxial compressive loading

$$\sigma_{cr} = k \frac{\pi^2 E}{12\left(1-\nu^2\right)\left(\frac{b}{t}\right)^2} \tag{13}$$

The buckling coefficient k is a function of the type of stress (in this case uniform compression on two opposite edges) and the edge support conditions (in this case simple support on four edges), in addition to the aspect ratio b/a. Values of k for various values of the aspect ratio b/a and for idealized edge conditions can be found in a number of textbooks relating to structural mechanics.

As in the case of the column, similar models can be developed for evaluating the buckling strength of unstiffened panel-doublers structures. However, the process is involved since plate-buckling problems are more complex than that of column buckling, and therefore, a thorough Finite-difference or finite-element analysis should be performed to evaluate and assess the buckling strength of the unstiffened panel-doubler plate structure as the doubler plate is placed at different locations within the unstiffened panel.

3.3. Example: Simple Formulation for Column with doubler plate (s)

Analytical formula based on the concept of equivalent rigidity of the column-doubler plate structure can be developed. It was evident from the results of both the finite-element and finite difference analyses of this study that a column with doubler plating has a much higher buckling load than that of a base column. Furthermore, the buckling load of the column-doubler structure is a maximum at the center and decreases as the location of the doubler plate x decreases from the end point of the column. Therefore, the rigidity of the column-doubler structure is a function of the location of the doubler plate along the length of the column, and also a function of the mechanical properties of both the doubler plate and the column.

Let $(I/L^2)_{eq}$ = equivalent rigidity of the column-doubler structure, and assuming that the modulus of elasticity for the column and the doubler plate is the same, then

$$\left(\frac{I}{L^2}\right)_{\text{eq}} \approx \left(\frac{I}{L^2}\right) + \frac{I_d}{a_d^2}\left[\frac{L/2-y}{L/2}\right]^n \tag{14}$$

where I_d = moment of inertia of the doubler plate, I_c = moment of inertia of the column, $I = I_d + I_c$, L= length of column, a_d = length of doubler plate, and n = exponent depends on the numerical results of either the finite-difference or the finite-element analyses. Therefore, the buckling strength of a column with doubler plate can be evaluated from

$$P = \pi^2 E\left(\frac{I}{L^2}\right)_{\text{eq}} \approx \pi^2 E\left(\left(\frac{I}{L^2}\right) + \frac{I_d}{a_d^2}\left[\frac{L/2-y}{L/2}\right]^n\right) \tag{15}$$

The exponent n can be set based on the results of the finite element or the finite difference analyses for a wide range parameters relating to both the column and the doubler plate. In a similar manner, simplified formula can be developed to predict the strength of uniaxially compressed unstiffened panel with doubler plates.

4. Case Studies

4.1. Effect of Welds, Corrosion, and Cracking on Column Strength

The main welds, corrosion, cracking, and in general discontinuity have great effect on column strength. The buckling load capacity of a column tends to decrease due to these damaging factors [3]. The purpose of this paper is to study these effects on the strength of column, with and without doublers, covering these cracks and holes.

Figure 5 shows critical buckling strength of damaged column structure as a function of the Degree of Corrosion (% of plate depth).

4.2. Effect of Doubler Location on the Critical Buckling Strength of Unstiffened Plate

The effect of doubler location on the critical buckling strength of unstiffened plate is illustrated in Figure 6. The values in the figure were based on the results of a finite-element analysis performed by the joint team effort of Martec and BMA Engineering [3].

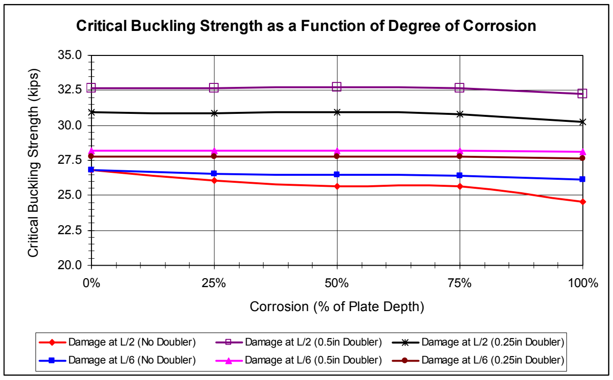

Figure 5. Critical buckling strength of damaged column structure as a function of the degree of corrosion (% of plate depth) [3]

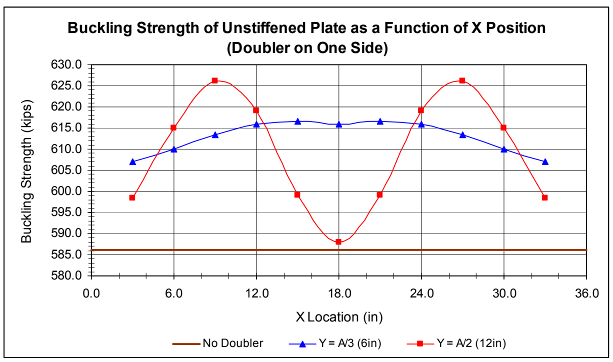

Figure 6. Effect of doubler location on the critical buckling strength of unstiffened plate (doubler on one side only) [3]

5. Reliability-based Partial Safety Factors for Unstiffened Panel with Doubler Plate (s)

As mentioned earlier, the second approach (LRFD) of reliability-based design consists of the requirement that a factored strength of structural component must be larger than or equal a linear combination of factored load effects as presented by the LRFD format of Eq. 2. For a uniaxially loaded and damaged unstiffened panel with doubler plate, partial safety factors were determined (for demonstration purposes) to satisfy the requirements of the LRFD general design formats for ship hull structural components as given by limit state 1 (Eq. 4) and limit state 2 (Eq. 5). These partial safety factors are provided in Tables 1 and 2 for limit sates 1 and 2, respectively. The factors were determined using FORM and based on previously established probabilistic characteristics of basic random variables for both the strength and the load. Eqs. 4 and 5 or Eqs. 7 and 8 can be used in conjunction with the partial safety factors provided in Tables 1 and 2 for the design or checking the adequacy of unaxially compressed unstiffened panel with doubler plate.

Table 1. Partial safety factors for limit state 1

β_0	ϕ_u	γ_{SW}	γ_{WD}
3.0	0.75	1.05	1.45
3.5	0.70	1.05	1.50
4.0	0.64	1.05	1.55

Table 2. Partial safety factors for limit state 2

β_0	ϕ_u	γ_{SW}	γ_W	γ_D
3.0	0.83	1.05	1.40	1.10
3.5	0.79	1.05	1.55	1.10
4.0	0.76	1.05	1.70	1.10

It is to be noted that the values for k_{WD}, k_W, and k_D that appear in Eqs. 4 and 5 or Eqs. 7 and 8 can be taken as 1.0, 1.0, and 0.7, respectively. Also, the strength variable R_n in the right-hand side of these equations is to represent the ultimate buckling nominal design stress (e.g., P/tb) for uniaxially compressed unstiffened panel with doubler plate (s).

Acknowledgments

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