



## **GUIDANCE NOTES ON**

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# **ICE CLASS**

**MARCH 2005 (Updated February 2014 – see next page)**

**American Bureau of Shipping  
Incorporated by Act of Legislature of  
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## Updates

### February 2014 consolidation includes:

- October 2008 version plus Corrigenda/Editorials

### October 2008 consolidation includes:

- March 2005 version plus Corrigenda/Editorials

## Foreword

The purpose of these Guidance Notes is to provide ship designers with clear guidance on alternative design procedures for hull side structures, on alternative methods for determination of power requirements, and on procedures for propeller strength assessment based on the Finite Element Method for Baltic Ice Class Vessels.

- Chapter 1 provides a procedure on ice strengthening designs using direct calculation approaches.
- Chapter 2 provides a procedure for the calculation of power requirement for ice class vessels.
- Chapter 3 provides a procedure for the strength analysis of propellers for ice class vessels.

This document is referred to herein as “these Guidance Notes” and its issue date is 31 March 2005. Users of these Guidance Notes are encouraged to contact ABS with any questions or comments concerning these Guidance Notes. Users are advised to check with ABS to ensure that this version of these Guidance Notes is current.

These Guidance Notes supersede the 2004 ABS *Guidance Notes on Nonlinear Finite Element Analysis of Side Structures Subject to Ice Loads*.

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# CHAPTER 1 Ice Strengthening Using Direct Calculation Approaches

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# CHAPTER 1 Ice Strengthening Using Direct Calculation Approaches

## SECTION 1 Introduction

### 1 Background

According to the Finnish-Swedish Ice Class Rules (abbreviated as “FSICR” in these Guidance Notes), it is stipulated that longitudinal frames shall be attached to all supporting web frames and bulkheads by brackets. In a subsequent paragraph, it is stated that “For the formulae and values given in this section for the determination of hull scantlings, more sophisticated methods may be substituted subject to approval by the administration or the classification society.”

Ice load measurements conducted with vessels navigating in the Baltic show that loads several times higher than the design loads are often encountered. It is deemed that designing up to the yield point with these high loads would be uneconomical, and so, some excess of the nominal design load is acceptable.

In certain extreme cases, some plastic deformation will occur, leaving behind a permanent set. The design of the longitudinal frames can be checked by using a FEM program capable of nonlinear structural analysis. In such an analysis, the permanent set can be calculated and the ultimate load-carrying capacity of the frames predicted.

The Finnish Maritime Administration (abbreviated as “FMA” in these Guidance Notes) released the “Tentative Note for Application of Direct Calculation Methods for Longitudinally Framed Hull Structure” (referred to as “FMA Guidelines” in these Guidance Notes) for alternative design of side structures using nonlinear FEM analysis. See Chapter 1, Appendix 3.

In 2004, ABS released the *Guidance Notes on Nonlinear Finite Element Analysis of Side Structures Subject to Ice Loads* to provide a procedure to design side longitudinals using a nonlinear FEM analysis. This publication incorporates the information in the 2004 Guidance Notes and supersedes that publication.

### 2 Purpose

The purpose of this Chapter is to clearly define a procedure for ice strengthening of side structures using nonlinear FEM, including both side longitudinals and side shell plating. In accordance with Ice Class Rules, the results of such an analysis may be used to substitute for standard Rules formulae. Certain design requirements, such as constraints on longitudinal frame spacing, the bracket attachment requirement between web frames and bulkheads and side shell thickness, may be relaxed.

These Guidance Notes provide more technical details to supplement the FMA Guidelines. In addition, these Guidance Notes provide a procedure for alternative design of side shell plate using nonlinear FEM. This may lead to relaxation of side shell plating thickness requirements compared to the FMA Guidelines.

### 3 Applications

The requirement that the maximum frame spacing of longitudinal frames “shall not exceed 0.35 meter for ice class **IA Super** and **IA** and shall in no case exceed 0.45 meter” stems from the fact that the ice loading is concentrated along a narrow horizontal strip, typically only 250 mm wide. In order to limit the possible catastrophic consequences of longitudinal frames collapsing, there is a Rule requirement to install brackets between longitudinal frames and transverse webs. These brackets increase the ultimate load-carrying capacity of the frames by effectively reducing their span. However, the installation of such brackets may lead to higher production costs, and it is desirable to use nonlinear FEM to justify a decision to omit such brackets in order to optimize structural design.

Nonlinear FEM is also used to optimize the design with a balanced strength between side shell plate and side longitudinals.

### 4 Key Components of these Guidance Notes

The key components of applying a nonlinear FEM analysis of side structures subject to ice loads include:

- Design procedure
- Nonlinear FE model, including structural idealization, material modeling, loading, solution, convergence requirements etc.

These analysis components can be expanded into additional topics, as follows, which become the subject of particular Sections in the remainder of this Chapter

### 5 Contents of this Chapter

Chapter 1 of these Guidance Notes is divided into the following Sections and Appendices:

- Section 1 – Introduction
- Section 2 – Procedure for Ice Strengthening Side Structures Using Nonlinear FEM
- Appendix 1 – Nonlinear FE Model
- Appendix 2 – Example of Nonlinear FEM Applications
- Appendix 3 – The Finnish Maritime Administration (FMA) “Tentative Note for Application of Direct Calculation Methods for Longitudinally Framed Hull Structure”, 30 June 2003

# CHAPTER 1 Ice Strengthening Using Direct Calculation Approaches

## SECTION 2 Procedure for Ice Strengthening Side Structures Using Nonlinear FEM

### 1 Design of Side Structures

The ice strengthening procedure involves four steps for alternative design of the side structure under ice load. These four steps are summarized in 1-2/Table 1 and are described in detail below.

**TABLE 1**  
**Steps in Ice Strengthening of Side Structures**

| Step | Design                                    | Notes                                                                                                           |
|------|-------------------------------------------|-----------------------------------------------------------------------------------------------------------------|
| 1    | FSICR design, baseline design             | Design fully complies with FSICR<br>(Ice strengthened longitudinal spacing, less than 450 mm)                   |
| 2    | FMA interim design                        | Design complies with the FMA Guidelines, item 2<br>(Longitudinal spacing is wider than that specified by FSICR) |
| 3    | Alternative design for side longitudinals | Side longitudinals without brackets are determined using nonlinear FEM.                                         |
| 4    | Alternative design for side shell         | Side shell thickness is determined using nonlinear FEM for extreme ice loads.                                   |

### 2 Step 1: FSICR Design

The initial design of side structures should fully comply with FSICR. FSICR require that the maximum frame spacing of longitudinal frames “shall not exceed 0.35 meter for ice class **IA Super** and **IA** and shall in no case exceed 0.45 meter”. Brackets are required to connect longitudinals and webs.

### 3 Step 2: FMA Interim Design

FMA interim design uses the FMA Guidelines to design side structure with longitudinal spacing about 800 millimeters. The ice pressure is higher than that of FSICR. Brackets are needed to connect longitudinals and webs.

The side shell plating thickness is calculated following the FMA Guidelines (see Chapter 1, Appendix 3), as in the equation below:

$$t = 667 \cdot s \cdot \sqrt{\frac{p_{PL}}{f_2 \cdot \sigma_Y}} + t_c \quad \text{mm}$$

where  $p_{PL}$  is the ice pressure acting on the side shell plating. The details of this equation can be found in the FMA Guidelines (1-A3/2.1).

### 4 Step 3: Alternative Design for Side Longitudinals

Alternative structures shall follow the FMA Guidelines to ensure equivalency in permanent deformation of the side longitudinals. Nonlinear FEM can be applied to evaluate this equivalency. Structural modeling is to follow the procedure in these Guidance Notes. The permanent deformation of the side longitudinals should be checked by the acceptance criteria in 1-2/4.3. The details of this step, including the FEM modeling, load applied and acceptance criteria, are described below.

#### 4.1 FEM Modeling

The FEM modeling procedure and boundary condition requirements are described in Chapter 1, Appendix 1. Other details about FEM, including FEM solution and convergence requirements can also be found in Chapter 1, Appendix 1.

#### 4.2 Ice Load on Side Longitudinals

For the purpose of designing a side longitudinal and its end connections to web frames, the ice loads may be represented as line loads acting on the longitudinal within the ice belt. The load applied to the FE model is described in detail in 1-A1/4.

#### 4.3 Acceptance Criteria

FMA recommends "... that the shell structure is modeled both for the rule requirements with brackets and for the proposed structure without brackets. If the plastic deformation for the proposed structure is equal to or smaller than for the rule structure, the scantlings of the proposed structure may be considered acceptable." (See Chapter 1, Appendix 3.)

The proposed unbracketed design is to be compared with the FMA interim design. The Finite Element procedures outlined in these Guidance Notes should be used to perform the analysis of both bracketed and unbracketed designs. If an unbracketed longitudinal scantling can be shown to resist plastic deformation such that it results in permanent deformation that is either equal to or less than the Rule bracket design, the unbracketed design can be accepted. The FSICR initial design and FMA interim design can be used as the benchmark for this comparison.

## 5 Step 4: Alternative Design of Side Shell

Alternative design of side shell plating thickness may also be accepted if the resulting permanent deformation of shell plating subject to extreme ice loads falls within an acceptable range. Nonlinear FEM analysis is to be performed to calculate the permanent deformation of the side shell plating. The side longitudinal is the same as the FMA alternative design as in Step 3. Permanent deformation of the side shell plating is to be checked by the acceptance criteria in 1-2/5.3 to determine the reasonable side shell thickness.

### 5.1 FEM Modeling

The FE model is the same as the FMA alternative design in Step 3, following the same requirements in Chapter 1, Appendix 1, with the same side longitudinals. The side shell thickness may be reduced based on the thickness requirement calculated from the FMA Guidelines in Step 3. The boundary conditions and convergence requirements are the same as those in Step 3.

### 5.2 Ice Load on Side Shell

Ice loads are to be modeled as patch loads and be applied to the side shell between supporting structures. These extreme ice loads are calculated based on the following guidelines:

- Pressure equal to 3 times the ice pressure for plating in the FMA Guideline
- Length of patch loads equals 2 times longitudinal spacing.
- Load height equals that defined in FSICR.

The load applied to the FE model is explained in 1-A1/5.

### 5.3 Acceptance Criteria

Permanent deformation of the side shell between longitudinals up to 2% of longitudinal spacing is acceptable. However, in no case can the thickness before the abrasion/corrosion margin is added be less than 90% of the current FMA requirement, as in the FMA alternative design (Step 2).

### 5.4 Abrasion/Corrosion

The increment for abrasion/corrosion of 2 millimeters must be applied to the side shell plate unless special treatment is applied to the hull surface. This abrasion/corrosion margin is to be added to the thickness as calculated.

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# CHAPTER 1 Ice Strengthening Designs Using Direct Calculation Approaches

## SECTION 3 References

ABS, 2004. *Guidance Notes on Nonlinear Finite Element Analysis of Side Structures Subject to Ice Loads*. American Bureau of Shipping, April 2004.

ABS, 2005. *Rules for Building and Classing Steel Vessels*. American Bureau of Shipping, 2005

FMA, 2002. *Finnish-Swedish Ice Class Rules*

FMA, 2003, *Tentative Guidelines for Application of Direct Calculation Methods for Longitudinally Framed Hull Structure*, FMA, issued 30 June 2003.

FMA, 2004, *Guidelines for the Application of the Finnish-Swedish Ice Class Rules*, FMA, draft 19 November 2004

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# CHAPTER 1 Ice Strengthening Designs Using Direct Calculation Approaches

## APPENDIX 1 Nonlinear FE Model

### 1 Structural Idealization

#### 1.1 Introduction

In order to create a three-dimensional model that can be analyzed in a reasonable amount of time, a subsection of the vessel's side structure is considered. Indeed, as long as enough structure is modeled to sufficiently move the boundary effects of fixity away from the area of interest, there is no benefit in modeling a greater area of the vessel structure. The result on the longitudinal frame of interest will remain the same, although the analysis time could increase substantially.

#### 1.2 Extent of Structural Modeling

The three-dimensional structural model is to be justified as being representative of the behavior of side structures subject to ice loads.

- i) *Longitudinal direction.* In principle, the structural model is to extend a minimum of three webs (three-bay model) with an extra half-frame spacing on the forward and aft ends.
- ii) *Vertical extent.* In principle, the structural model is to extend between the two horizontal stringers that include the ice belt region. Typically, the ice belt is applied in the area of a single longitudinal frame that is halfway between the stringers. The model should contain at least one three-dimensional longitudinal frame above and below the frame of interest. Modeling more than three three-dimensional longitudinal frames will require more time for modeling and analysis with little to no appreciable difference in the result.
- iii) *Transverse direction.* The FE model extends to and includes the inner skin.

Structures to be modeled include:

- Side shell plating and side longitudinal frames
- Web frames, web stiffeners and brackets, if any
- Inner skin plating and attached longitudinals

#### 1.3 FEM Elements

Shell elements are generally used for representing the side shell, inner skin, web frames and web and flange of the side longitudinal within the ice belt.

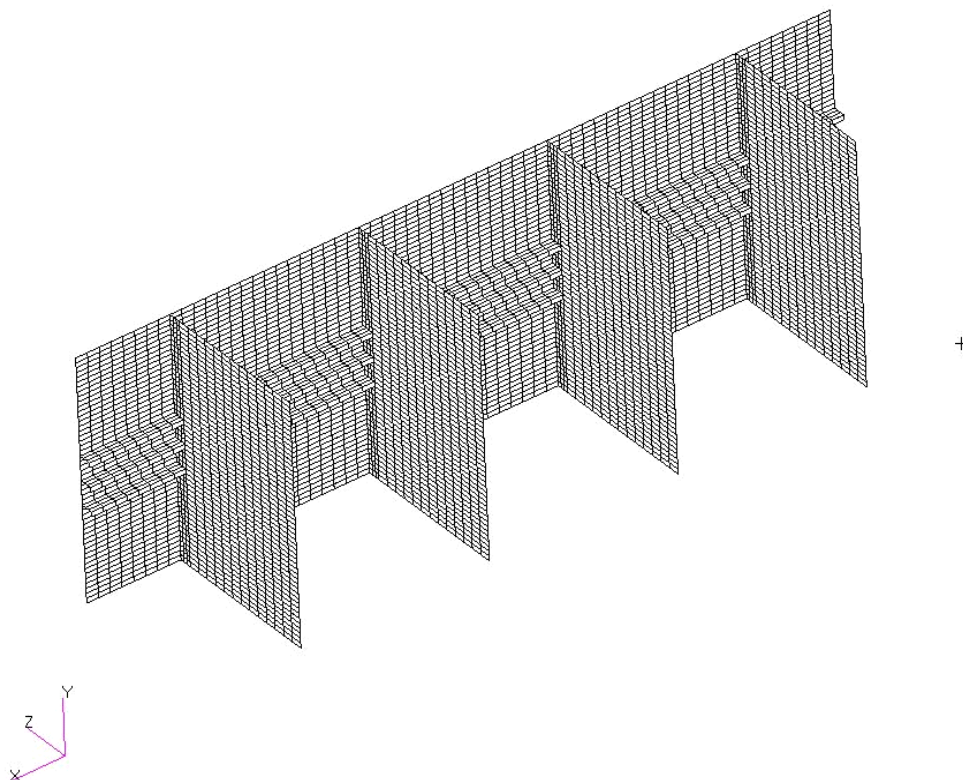
Beam elements can be used for side longitudinals outside of the ice belt.

The flange of the side longitudinals within the ice belt can be modeled using either shell elements or beam elements.

## 1.4 Mesh Size

Mesh size should be selected such that the modeled structures reasonably represent the nonlinear behavior of the structures. Areas where high local stress or large deflections are expected are to be modeled with fine meshes. 1-A1/Figure 1 shows an example of the FEM mesh.

**FIGURE 1**  
**FE Model Extent (Inner Skin Removed for Clarity)**



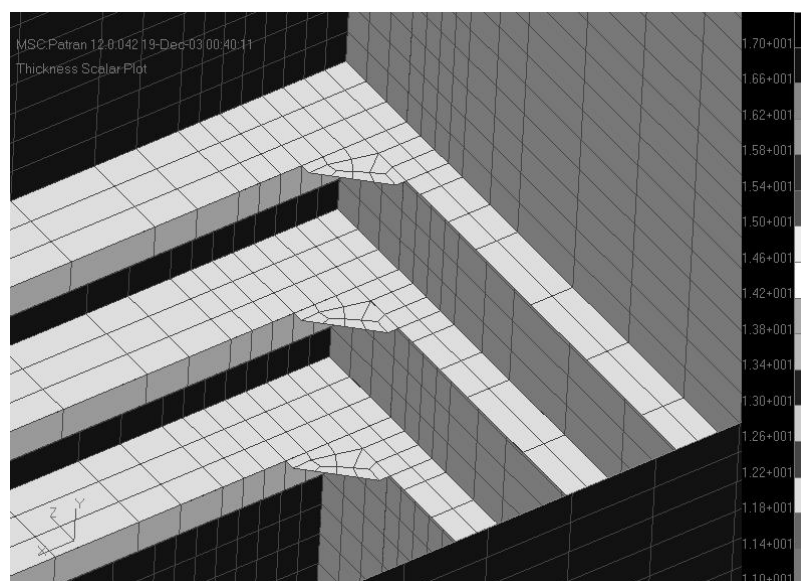
It is preferable to use quadrilateral elements that are nearly square in shape. The aspect ratio of elements should be kept below 3-to-1.

In general, the web of a longitudinal is to be divided into at least three elements (see 1-A1/Figure 2). The flange of a side longitudinal can be modeled by one shell element or by a beam element.

The side shell, web frames and inner skin can be divided into elements that are of the same size as that for the web of side longitudinal. Structures away from the ice belt may be represented using a coarser mesh. Tapering of fine mesh to relatively coarse mesh is acceptable.

When modeling brackets, the mesh should be finer in order to carry at least three elements in the area where the bracket meets the longitudinal flange (see 1-A1/Figure 2). It is recommended to keep element edges normal to the bracket boundary and avoid using triangular-shaped elements. Also, it is preferable not to use quadrilaterals oriented in such a way that only one point touches a bracket boundary.

**FIGURE 2**  
**Mesh of Side Longitudinal and Bracket at Connection to Web Frame**



## 2 Material Model

Material nonlinearity results from the nonlinear relationship between stress and strain once the elastic yield limit of the material has been reached. The behavior of materials beyond yield is typically characterized by the slope of the stress-strain curve that indicates the degree of hardening. In general, it is recommended to use an elastic-perfectly-plastic material model for shipbuilding steel that does not account for strain hardening effects. This simplification yields conservative results.

The elastic-perfectly-plastic material model for mild steel is characterized by the following parameters:

|                           |             |
|---------------------------|-------------|
| Yield Stress              | 235 MPa     |
| Young's Modulus (elastic) | 206,000 MPa |
| Poisson's Ratio           | 0.3         |

## 3 Boundary Conditions

The boundary conditions constrain the model in space while permitting the longitudinal frame to flex as it would if the entire structure had been modeled.

1-A1/Table 1 and 1-A1/Figure 3 show the recommended boundary conditions.

- The top and bottom cut planes (ADHE and BCGF) apply complete translational fixity, but allow rotation about the vessel's longitudinal axis. This represents the rigidity of the horizontal stringers bounding the vertical model extent.
- The forward and aft cut planes (ABCD and EFGH) apply a symmetric condition with respect to the plane perpendicular to the vessel's longitudinal direction. This represents that the structure is continuous in the vessel's longitudinal direction.

**FIGURE 3**  
**Boundary Conditions for FE Model**

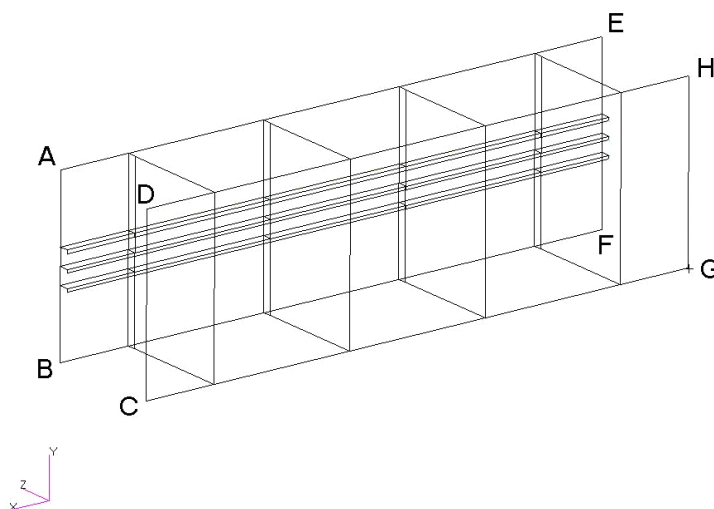


**TABLE 1**  
**Boundary Conditions for FE Model**

| <i>Boundary of FE model</i>        | <i>Planes ADHE, BCGH<br/>(top and bottom ends)</i> | <i>Planes ABCD, EFGH<br/>(fore and aft ends)</i> |
|------------------------------------|----------------------------------------------------|--------------------------------------------------|
| Displacement in <i>x</i> direction | Constrained                                        | Constrained                                      |
| Displacement in <i>y</i> direction | Constrained                                        | ---                                              |
| Displacement in <i>z</i> direction | Constrained                                        | ---                                              |
| Rotation in <i>x</i> direction     | ---                                                | ---                                              |
| Rotation in <i>y</i> direction     | Constrained                                        | Constrained                                      |
| Rotation in <i>z</i> direction     | Constrained                                        | Constrained                                      |

*Note:*

The *x*, *y* and *z* directions are the vessel's length, depth and transverse direction, respectively.

## 4 Line Load on Side Longitudinals

The ice load is to be determined in accordance with the FMA Guidelines, item 3. For the purpose of designing a side longitudinal and its end connections to web frames, the ice loads may be represented as line loads acting on the side longitudinal within the ice belt (see 1-A1/Figure 4).

Typically, the extreme ice pressure,  $p_{\max}$ , to be applied to the model is calculated from the following formula:

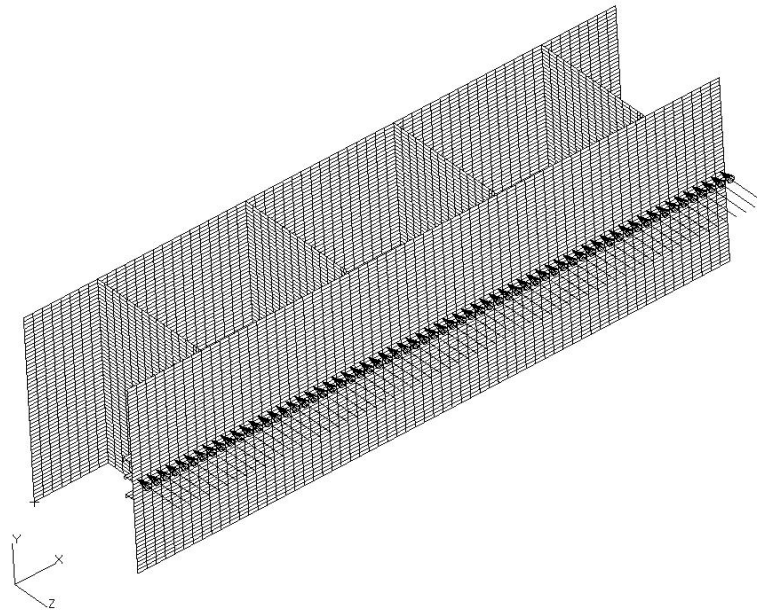
$$p_{\max} = 3.37c_d c_1 p_0 (1.059 - 0.175L)$$

Refer to the FMA Guidelines (also included in Chapter 1, Appendix 3) for the details of the ice pressure calculation.

The line load,  $Q$ , is the maximum ice pressure,  $p_{\max}$ , multiplied by the load height,  $h$ , which is applied to the side shell longitudinal along the model length:

$$Q = p_{\max} * h \text{ N/mm}$$

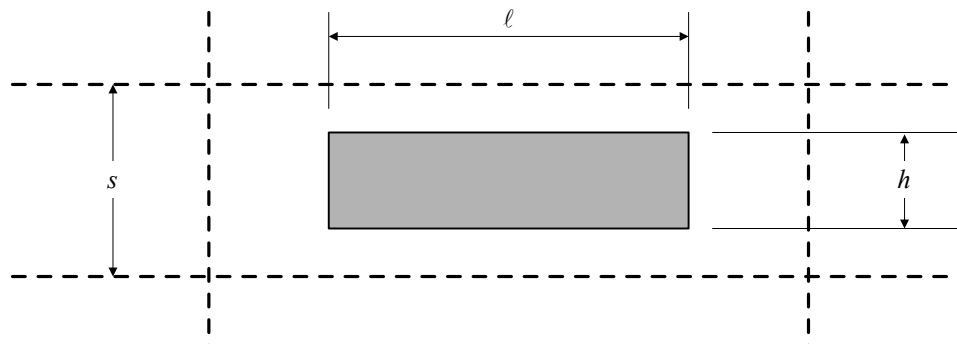
**FIGURE 4**  
Ice Load as Line Load on Side Longitudinal



## 5 Patch Load on Side Shell Plate

The side shell plate is subject to a patch ice load defined by  $p$  (ice pressure for shell plate),  $h$  (load height)  $\times \ell$  (load length), as indicated in 1-A1/Figure 5. Load height  $h$  is to be defined according to FSICR or 6-1-6/11.5 of the ABS *Rules for Building and Classing Steel Vessels*. Load length  $\ell$  is to be two times the longitudinal spacing.

**FIGURE 5**  
Ice Patch Load Applied on Side Shell Plate



The applied extreme ice pressure having the following format is three times the design ice pressure defined in the FMA Guidelines:

$$p = 3 \cdot c_d \cdot c_1 \cdot c_a \cdot p_0$$

The details of this equation can be found in the FMA Guidelines, FSICR and 6-1-6/11.7 of the ABS *Rules for Building and Classing Steel Vessels*.

## 6 FEM Solution

### 6.1 Incremental Solution

The nonlinear analysis employs a nonlinear static analysis with gradually increasing loads. The basic approach in a nonlinear analysis is to apply loads incrementally until the solution converges to the applied loads. Therefore, the load increment should be sufficiently fine to ensure the accuracy of the prediction.

### 6.2 Convergence

The convergence test is an important factor that affects the accuracy and overall efficiency in nonlinear finite element analysis. In order to ensure accurate and consistent convergence, multiple criteria with errors measured in terms of displacement, load and energy should be combined. The convergence test is performed at every load step.

Although there are no universally-accepted criteria, some tolerance criteria have been proposed for controlling the calculation errors in each load step. The goal of the tolerance criteria is to consistently provide sufficiently accurate solutions to a wide spectrum of problems without sacrificing calculation efficiency.

For example, the following tolerance criteria are recommended in the MSC Handbook for Nonlinear Analysis.<sup>1</sup>

- Error tolerance for displacement is less than  $10^{-3}$ .
- Error tolerance for loads is less than  $10^{-3}$ .
- Error tolerance for energy/work is less than  $10^{-7}$ .

The load step is assumed to converge when all three tolerance criteria are met.

If the solution does not converge, it is recommended that the number of load steps be increased rather than error tolerances relaxed.

## 7 Nonlinear FEM Theory and Software

### 7.1 Material Nonlinearity

Material nonlinearity is an inherent property of any engineering material. Material nonlinear effects may be classified into many categories, such as plasticity, nonlinear elasticity, creep and viscoelasticity.

The primary solution operations are gradual load increments, iterations with convergence tests for acceptable equilibrium error and stiffness matrix updates.

<sup>1</sup> MSC/NASTRAN Handbook for Nonlinear Analysis, Sang H. Lee, The MacNeal-Schwendler Corporation

## 7.2 Geometrical Nonlinearity

Geometrical nonlinearity results from the nonlinear relationship between strains and displacement. Geometrical nonlinearity leads to two types of phenomena: change in structural behavior and loss of structural stability. As the name implies, deformations are large enough that they significantly alter the location or distribution of loads, so that equilibrium equations must be written with respect to the deformed geometry, which is not known in advance.

## 7.3 Incremental Solutions

Nonlinear analysis is usually more time-consuming and requires more data input than linear analysis. The nonlinear solution, if yield stress is exceeded, will require a series of iterative steps where the load is incrementally applied. Within each load step, a series of sub-iterations may be required in order to reach equilibrium convergence with the current load step.

The basic structure of the iterative schemes utilized in nonlinear analyses is bimodal. There is a predictor algorithm in the scheme which produces initial guesses of the nonlinear stiffness matrix. Subsequently, a corrector scheme is utilized for the determination of the updated response. This response, determined through the corrector scheme, is subsequently utilized in the determination of the relative error in the convergence criterion and a new cycle of prediction/correction starts until the set criteria are satisfied. This cyclic sequence of computations constitutes a series of iterations within an increment. It is repeated until the total load is applied.

The nonlinear iteration methods include the Newton-Raphson method denoted, the modified Newton-Raphson method and the arc length family of methods.

## 7.4 Convergence Criteria

Choice of convergence criterion depends on the type of structure, degree of accuracy required and efficiency in the solution process. A combination of convergence criteria based on the out-of-balance load and change in displacement is ideally suited for the pre-yielding part of the simulation. For the post-yielding phase, the displacement based convergence criterion can be relaxed because displacement is very high after yielding.

## 7.5 Commercial FEM package

Many commercial FEM packages offer the capability of nonlinear analysis. The most widely-used FEM packages are: NASTRAN and MARC from MacNeil-Schwendler Corporation, ANSYS from Swanson Analysis and ABAQUS from Hibbits, Karlson and Sorenson, Inc.

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