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Research Article

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Deformation-Based Design Method of Aluminium Helideck for Eurocode 9

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Abstract

Aluminium alloys are increasingly used in the construction industry, as they offer high strength-to-weight ratios, good durability and ease of fabrication. An aluminium helideck structure should satisfy the requirements of offshore regulations and rule notations such as the Australian/New Zealand Standard and EUROCODE 9, in which the width-to-thickness ratio and yield stress are the recognised governing parameters for the design of cross-sections. Aluminium helideck structures are composed of several structural units, which can be aluminium or steel. The aluminium parts are the pancake, girder, safety net, etc. In this study, the aluminium helideck design with the relevant EUROCODE 9 is based on the strength calculation. It may be possible to reduce the calculation time and thus provide a reasonable solution in terms of a practical design. The static and nonlinear collapse behaviour of a developed structure is investigated in this study. The primary aim is to provide a reasonable solution that can improve product quality by checking both strength and deformation criteria. The effect of deflection during the fabrication stage is considered in the structural design based on the newly proposed EUROCODE 9. Lastly, a comparison between the results of this study and those from finite element analysis is presented.

Keywords: Aluminium helideck; Structural safety; Deformation-based design; Offshore installation; Eurocode 9

Introduction

The number of large offshore structures and platforms is rapidly increasing as demand for offshore oil increases. A helideck is installed in these offshore structures for helicopter landing and take-off. Offshore structures can be considered as primary areas of application for aluminium alloys in the future. These alloys offer many benefits to the offshore industry in the forms of cost savings, ease of fabrication and proven performance in hostile environments. Stair towers, mezzanine flooring, access platforms, walkways, gangways, bridges, towers and cable ladder systems can all be constructed in pre-fabricated units for simple assembly offshore or at the fabrication yard [1].

Helidecks have been made from aluminium alloy since the early 1970s and are thus fully tried and tested. They are designed to be modular with bolted connections, which enable them to be erected rapidly and easily handled and shipped. They also offer weight reduction of up to 70% over steel, meet the highest safety standards and provide a cost savings of up to 12%.

In structural applications, 6000 series alloys are commonly used due to their favourable combination of properties. The 6082 alloy is a relatively new aluminium alloy, and is popular in Europe and used extensively in America [2]. The alloy provides a superior combination of properties, such as high strength after heat treatment, satisfactory corrosion resistance, good machining properties and good weld ability [3]. The 6082 alloy has a higher strength than the classic and widely used 6061 alloy (0-8% higher for characteristic values of tensile ultimate strength, depending on product form and alloy temper, provided by Eurocode 9 [4]), a better general corrosion resistance, and is approximately equivalent in terms of other properties such as density, extrude ability and anodizing response [2].

In the engineering stage, the aluminium structure should be designed to international standards such as ISO codes [5], Eurocodes or national standards like NORSOK [6] or API [7]. Various offshore structures with typical octagonal helidecks are shown in Figure 1.

A brief review of research related to structural engineering for aluminium members is presented as follows. Mei-Ni Su et al. conducted

Figure 1: Helideck installation and configuration in offshore installations.

two series of simply supported bending tests on square and rectangular aluminium alloy hollow sections [1]. The test programme comprised 14 3-point and 15 4-point bending tests. The combined dataset from the tests and the numerical simulations were used to assess the accuracy of three international design specifications: The Aluminium Design Manual, the Austalian/New Zealand Standard and Eurocode 9 and the Continuous Strength Method (CSM) for predicting the moment capacity of simply supported aluminium alloy beams. Through a deformation-based approach incorporating strain hardening, the continuous strength method was shown to offer improved predictions of capacity, up to 30% beyond those achieved in current specifications.

Yujin Wang et al. performed a series of tests on the stability of heat-treated aluminium alloy 6082-T6 circular tube columns to check the reliability of buckling strength predictions using current design rules [8,9]. These comparisons illustrate that the American Aluminium design manual predictions are too conservative for small slenderness

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ratios, the Australian/New Zealand Standard predictions are unsafe for large slenderness ratios, the Eurocode 9 predictions are conservative and the Rasmussen-Rondal formulation provides the closest, generally conservative strength predictions.

Ye and Moan investigated the static and fatigue behaviour of three types of aluminium box-stiffener/web connections [10]. Their aim was to provide a connection solution that would reduce fabrication costs by changing the cutting spaces on the web frame and correspondingly the weld process, thus achieving sufficient fatigue strength. Finite element (FE) analysis identified the influence of local geometry and weld parameters on the stress gradient near the fatigue cracking area. The influence of the weld parameters on the structural stress concentration factors was also studied.

The aluminium helideck structure consists of the pancake, girder and steel supporting members, as shown in Figure 2. Structural engineers must consider all possible basic loads and load combinations. The governing load is impact-induced when helicopter landing takes

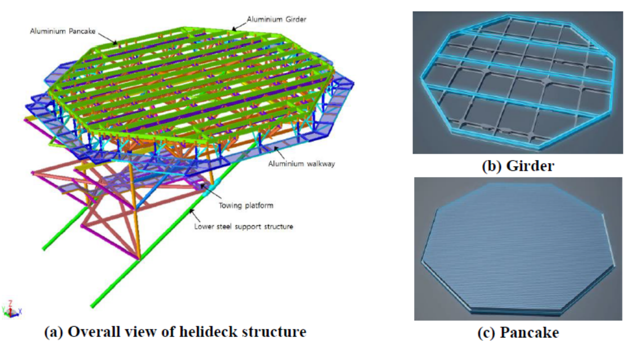

Figure 2: Helideck construction.

Type of helicopter	Sikorsky S-92
Maximum Take-Off Weight (MTOW)	12,565 kg
Crew	2 (pilot, co-pilot)
Length	17.10 m
Width	5.26 m
Height	4.71 m
Distance between wheels	3.18 m
Applied contact area	300 × 300 mm = 90,000 mm²

Table 1: Helicopter specification.

Vertical impact load per wheel (Emergency)	200.8 kN
Vertical impact load per wheel (Operating)	123.6 kN
Lateral impact load	61.8 kN

Table 2: Impact loads induced by helicopter landing.

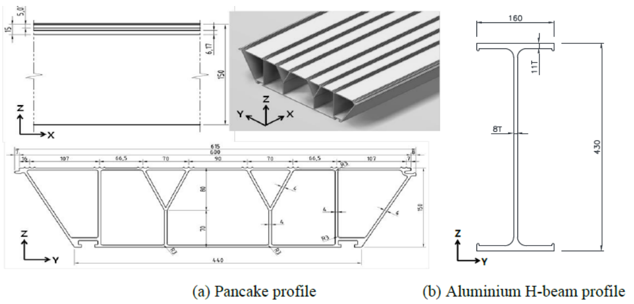

Figure 3: Aluminium pancake profile with Y-cores and girder profile [12].

Area of cross-section	A	7,134 mm²
Inertia moment about Y-axis	I_y	213,882,693 mm⁴
Inertia moment about Z-axis	I_z	7,985,029 mm⁴

Table 3: Section properties of aluminium H-beam profile.

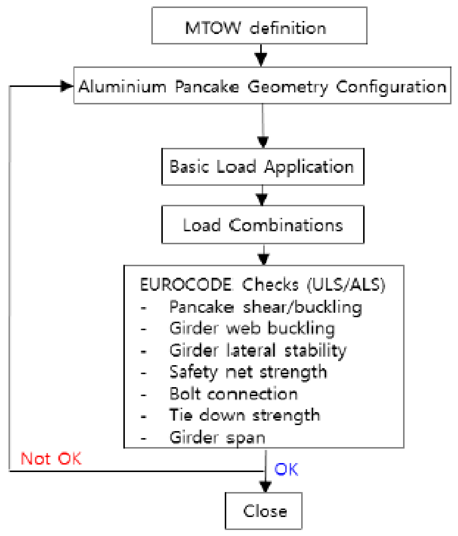

Figure 4: Flow chart for design process by classical Eurocode 9.

place, and the helideck structure has to sustain and cope with imposed loads on the deck from personnel, freight, refuelling and other temporary equipment; environmental loads from wind, snow, ice and rotor downwash; and its own self-weight [11].

The codes and standards applicable to the specific structural design of the aluminium helideck are determined by where the helideck is to be operated and the national jurisdiction governing the installation.

In this study, we review the current structural design method for Eurocode 9. The current industrial practice is to select the helideck design most suitable for offshore conditions. Some of the design factors in the code with reference to the structural engineering stage of aluminium helidecks are not clearly determined, so new engineering decisions on these factors and the methodology required must be developed. The main objectives of the study are to develop a reasonable procedure to estimate the structural safety of an aluminium structure and to propose a design based on deformation for aluminium helidecks under an impact load.

Objective of the Aluminium Helideck Design Procedure

Target structures and design parameters

The target helicopter is a Sikorsky S-92 with a MTOW (Maximum Take-Off Weight) of 12.6 tons and a rotor diameter value of 20.88 m, as indicated in Table 1.

The governing load is the impact load induced by the helicopter landing and take-off action. For accident conditions, an impact load of 2.5 times the MTOW should be considered for the overall deck [11]. A lateral impact load of half the MTOW should also be considered in a helideck structure design (Table 2).

Aluminium pancake model

The developed aluminium pancakes have a profile 615 mm in breadth and 150 mm in height, as shown in Figure 3. The Y-shaped cores of the pancake are developed under consideration of efficiency in terms of extrusion and structural strength. The aluminium H-beam profile is defined as follows, giving the shape and dimension of the cross-section. The section properties for the H-beam profile are given in Table 3.

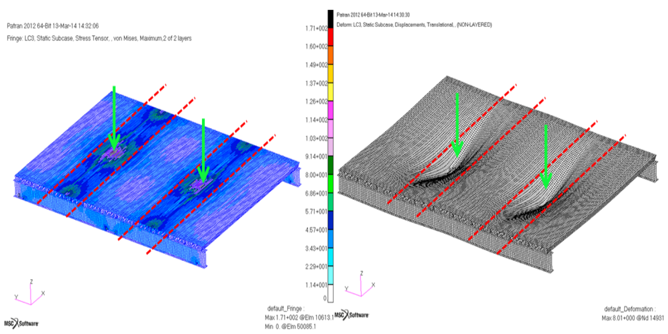

Figure 5: Defined effective pancake area based on FE analysis.

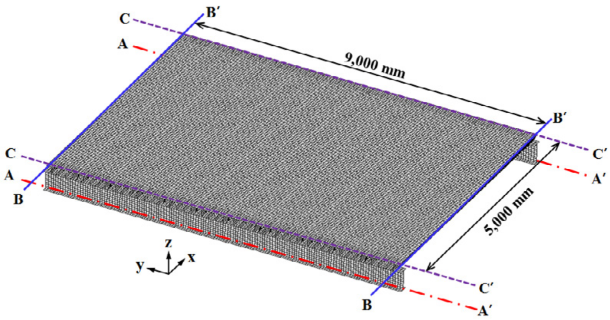

Figure 6: FE model of the aluminium pancake with H-beam girders.

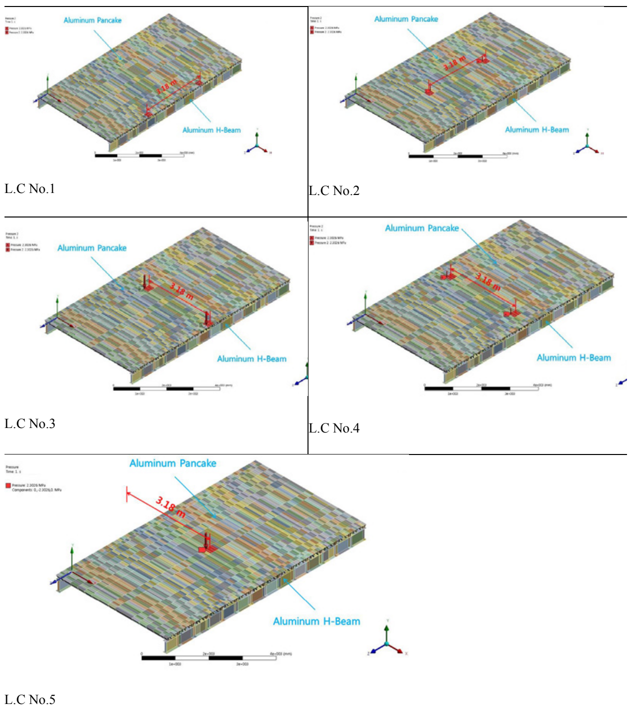

Figure 7: Load cases for FE analysis.

The evaluations of the structural safety and stability of the aluminium pancake are carried out by BS EN 19999-1-1:2007 to comply with the design requirement. Some design factors are not clearly defined in the codes and standards. Three-dimensional FE analysis is conducted to evaluate and define insufficient design factors by code, using the FE analysis programme 'ANSYS Mechanical APDL' developed by ANSYS Software Inc., USA [12,13].

Figure 4 shows the flow chart for the engineering process of the aluminium helideck structure by Eurocode 9.

Of the three methods suggested by the classical Eurocode 9, the first is a purely conventional approach based on a concentrated plasticity idealisation, which does not accurately correspond to the actual structural behaviour at collapse.

The second requires that the structure be calculated two times, once with a concentrated plasticity approach and again with a numerical simulation following the FE method. This results in a higher computation cost, which is not suitable for practical analysis of aluminium alloy structures without disregarding the actual mechanical features of the materials.

The inherent simplicity of the design means that it can be profitably used for structures at an ultimate limit state. From a practical viewpoint, it is quite similar to the classical plastic hinge method applied for steel structures. The Eurocode 9 provides some indications of the use of this method for the plastic analysis of structures by considering the actual mechanical properties of the different aluminium alloys.

In the structural engineering stage, which includes pancake shear and girder span checks, the number of pancakes is required, which is not clearly defined in Eurocode 9. To solve this undefined problem, the effective pancake areas are defined by FE analysis. The dashed red line in Figure 5 is the effective pancake area that takes the impact load induced by helicopter take-off action, which is a very important factor in the design stage.

Eurocode 9 proposes that both the Ultimate Limit State (ULS) and Accidental Limit State (ALS) be used to check the strength capacity and thereby the safety of the aluminium helideck structure, using load and material factors as per the specific conditions.

Numerical Analysis and Results

Finite element modelling

Simulation of the actual structural behaviour of the aluminium pancake requires several considerations. As the thin plate elements of structures are subjected to local and global buckling and the plate and vertical web are subjected to in-plane and out-of-plane buckling effects, the chosen element must be capable of modelling these buckling phenomena and the associated behaviour in both linear and nonlinear regions. This involves large displacements, elasto-plastic deformations and associated plasticity effects. A material constitutive curve using the Ramberg-Osgood law, based on the minimum requirements of the material (AL 6082-T6), is applied to the aluminium pancake.

A linear material model is satisfactory when only small quantities of the material are exposed to the yield stress or greater. Bilinear isotropic hardening is the constitutive law used to model the behaviour of steel. The bilinear isotropic hardening option uses von Mises yield criteria (which includes most ductile metals) coupled with an isotropic work-hardening assumption. This option is typically preferred for large strain analyses. In practical designs, engineers may want to know the safety

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factor of the structure for a nonlinear buckling load. Post-buckling analysis is required in such situations. The numerical simulations are carried out using the general commercial FE code ANSYS (ANSYS Inc. 2014). The ANSYS commercial programme, based on the FE method, provides a sparse direct solver for all nonlinear problems.

Boundary and load conditions

For the present nonlinear FE analysis, the helideck pancake model is applied in the span length (x) direction to accurately account for the effects of the rotational restraints along the edges (y), as described in Figure 6. This FE model is suitable for the geometric properties and structural behaviour of the panel considered here, as its panel deflection

LC No.	Maximum stress (MPa)	Allowable stress (MPa)	Safety Check
1	431.3	484.1	O.K
2	307.4	484.1	O.K
3	299.7	484.1	O.K
4	331.1	484.1	O.K
5	293.8	484.1	O.K

Table 4: Results of static FE analysis.

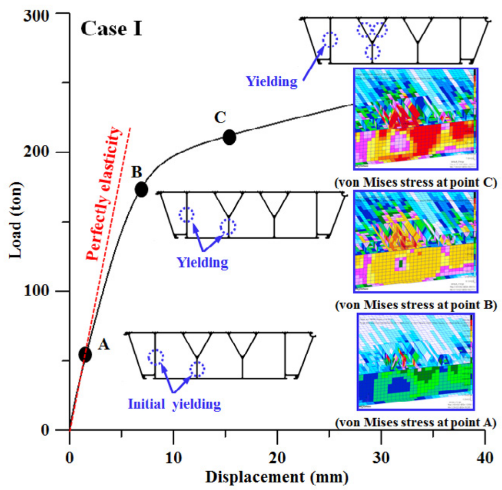
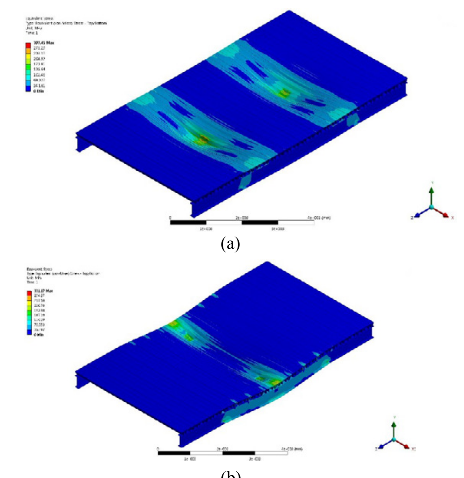


Figure 8: Progressive collapse behaviour of aluminium helideck structure.



(a) Loading condition No.2 (b) Loading condition No.4

Figure 9: Stress plot and deformed shape.

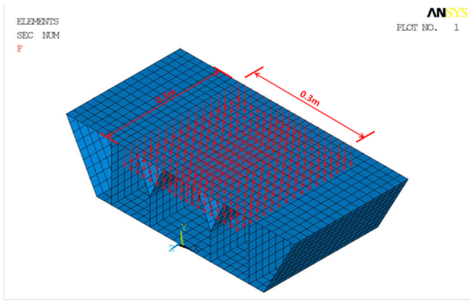


Figure 10: Loading diagram under vertical load.

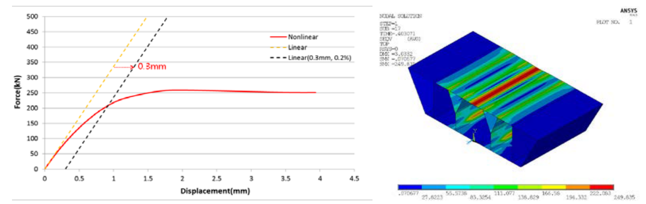


Figure 11: Relationships between the force and displacement curves under impact load.

behaviour is symmetrical between girders. In this study, we use one extreme edge condition, simply supported, along the longitudinal edges (or at the bottom girders).

The vertical landing force applied is 200.8 kN and the area of the landing force acting on the pancake is 90,000 mm². Five loading cases are considered to estimate the critical influence of the landing force on the vertical direction of the aluminium pancake, as shown in Figure 7.

Results

We analyse the structural safety of the aluminium pancakes and the aluminium girders using static analysis with regard to the landing force. The safety check results based on FE analysis are summarised in Table 4. The allowable stress is calculated as the allowable increase factor (1.33) × mesh size effect factor (1.4) × yield stress (260 MPa). On the basis of strength results, the maximum unity ratio of the structure is calculated as 0.89, whereas the allowable criterion is 1.0. The newly designed aluminium pancake therefore has sufficient strength to withstand the maximum landing force of 200.8 kN from the viewpoint of global yield strength. From a critical viewpoint, the structural behaviour must be verified using nonlinear structural analysis. As expected, the first yield point and buckling point occur at the Y-shaped webs. When the landing points are located in the middle of the pancake, the yield points are equally distributed along two Y-shaped webs in the pancake. The yielding at the Y-shaped web occurs before the pancake buckling in both cases, as shown in Figures 8 and 9.

We analyse the safety of the pancake via static analysis, depending on the landing positions. From the FE results, the maximum stress of the pancake is calculated as 431.3 MPa. The allowable stress of 484.1 MPa for the pancake member and aluminium girder is still sufficient, compared with the maximum stress of 431.3 MPa.

For nonlinear buckling analysis, we consider the maximum vertical force applied on the upper plate of pancake, as shown in Figure 10. These vertical forces are applied to the unit load for the linear buckling analysis. There is ultimate load of 500 kN for the nonlinear convergence buckling analysis, where the applied area of force is 90,000 mm².

We conduct elasto-plastic large deflection analysis to clarify the fundamentals in progressive collapse behaviour, including the occurrence of buckling/yielding of the thinner aluminium pancake under impact load. The load and displacement relationships are summarised in Figure 11.

In advanced aluminium structural design, load-carrying capacity calculations of members should consider post-weld initial imperfections as parameters of influence. Here, an initial tolerance value of maximum 0.5 mm per thickness is considered during the extrusion process, as there is no welding construction. The initial buckling mode obtained by Eigenvalue analysis through the FE method is used as the initial deflection mode.

First, the progressive collapse behaviour of a thin deck plate subjected to a compressive load is described in Figure 11. The initial yielding takes place at the 100-kN point, and the load-carrying capacity rapidly decreases due to the progressive yielding distribution at the centre plate.

Discussion on the Proposed Design Procedure based on Deformation

Deformation-based design

Figure 12 illustrates the engineering procedure with deformation-based design for the aluminium helideck proposed by the author. Determining the reasonable deformation criteria under impact landing and then re-verifying the FE-calculation is an important step.

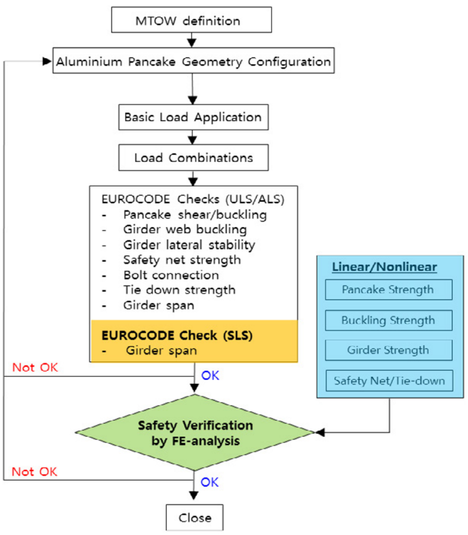
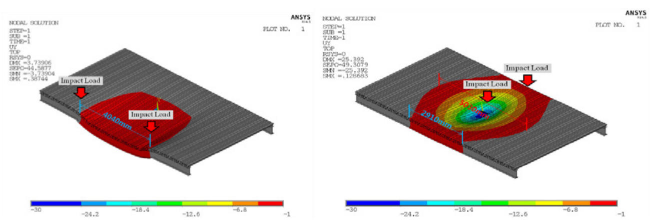


Figure 12: Flow chart for new design process.

Rule	Allowable deflection of cantilever (mm)	Allowable deflection of simply supported condition (mm)
NORSOK C004	Length/180	-
Present study	Length/150	Length/300

Table 5: Comparison results between NORSOK and the newly proposed criteria.



(a) Loading condition No. 1 (b) Loading condition No. 3

Figure 13: Global deflection shape and distribution.

Variables	Maximum deflection (mm)	Allowable deflection (mm)	Effective length (mm)	Clamping condition
LC.1	3.7	13.5	4,040.0	S.S*
LC.2	4.4	13.1	3,918.0	S.S
LC.3	25.0	33.5	5,030.0	CA**
LC.4	14.0	31.2	4,676.0	CA
LC.5	25.0	34.4	5,160.0	CA

Notes: *SS: Simply supported condition, **CA: Cantilever condition

Table 6: Results of global deflection check according to landing positions.

The NORSOK Standard is recommended, and the allowable global deflection of the cantilever length during helicopter landing and the comparison results between NORSOK and the newly proposed criteria are indicated in Table 5.

The global deflection shape and distribution under the impact load induced by helicopter take-off action are shown in Figure 13. Before determining the effective length against the impact load, we conduct a linear static FE calculation based on varying loading scenarios and an estimation of allowable deflection. Based on the preceding insights, the allowable deflection criteria may be empirically derived by FE calculation, as indicated in Table 5. The newly proposed criteria can be applied to the aluminium structural design by considering the material characteristics and the structural behaviour (Table 6).

Conclusions and Remarks

The goals of this study are to provide an engineering procedure with a deformation-based design to satisfy helideck safety requirements, and to perform a numerical calculation to verify a procedure based on the deformation criteria. A series of linear/nonlinear FEM analyses are conducted to investigate the buckling/progressive collapse behaviour and the strength of the aluminium pancakes with supporting girders subjected to landing load.

The study focuses on two areas, which are examined theoretically and numerically as appropriate: developing a reasonable procedure to estimate the structural safety of aluminium structure, and proposing a deformation-based design for the aluminium helideck under an impact load.

The following results and conclusions are developed in the study.

1) The proposed deformation criteria are empirically derived from numerical results and varying loading positions, and the accuracy of formulas for predicting allowable displacement are confirmed by comparing the NORSOK criteria and the calculated results with the FE analysis results.

2) Elastic stress sharply increases with the decrease in the mesh size of the element. To overcome this phenomenon in the convergence test, the allowable stress should be adjusted according to mesh size.

3) A deflection criterion can give a reasonable estimation of structural safety under a variety of loading conditions. The outcomes can be broadly applied in the aluminium basic design to decide the required span length during the code check stage.

4) The initial yielding is the governing parameter in determining the capacity of a thinner aluminium pancake under the impact load.

Acknowledgments

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