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STRENGTH ESTIMATION METHOD FOR UNDAMAGED, DAMAGED AND REPAIRED HONEYCOMB STRUCTURES

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Abstract

In Russia the change from a government based economy to market led economy has meant that all industries have had to re-assess their working practices to improve their economic efficiency. The airline industry is no exception and aircraft maintenance has been highlighted as a major source of expenditure where significant savings could be made. Inspection of the maintenance records from one repair bureau's work on Il-76 cargo aircraft revealed that the trailing edge flaps, of aluminium honeycomb construction(1), were being replaced rather than repaired probably because of the lack of a suitable analysis tool. The programme "SOTA" was therefore conceived as an analysis tool usable by medium rank specialists at a repair shop. It was decided to adopt a modular approach to the programme design so that the needs of different end users may be accommodated without compromise. This paper describes the first stage in the process of developing the programme "SOTA" which was to establish a foundation of an algorithm based on a simplified theory. From this foundation refinements will be made but only those for which the added complexity (and hence increased computer specification) can be justified in practical applications.

Introduction

The present work was begun to meet the specific need of analysing damaged trailing edge flaps on the IL-76 civil transport aircraft (Figure 1) identified by one repair bureau based at Bykovo* Airport. Figure 2 shows the damage distribution recorded by the bureau in the period 1990-1993 representing 78 areas of damage (excluding corrosion) on 33 aluminium honeycomb parts of 18 IL-76 aircraft in civil cargo operation(2). About 60% of this data relates to trailing edge flaps.

Figure 1 Ilyushin IL-76 Aircraft

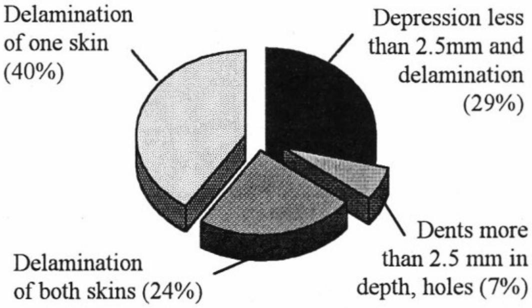

Figure 2 Honeycomb damage data excluding corrosion (IL-76)

It should be noted that, although the data presented is very limited, the IL-76 can be considered typical of aircraft in civilian service as it operates throughout all the Russian and former Soviet Union regions and has experience of the full range of weather and runway conditions.

Figure 3 shows the distribution of damaged honeycomb parts on the IL-76. Out of the 33 parts damaged 17 were replaced (12 parts with a single damaged area).

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* Bykovo Airport is one of the five major airports near Moscow. It is used mainly for commuter flights, transit flights North East / South East Russia and cargo flights.

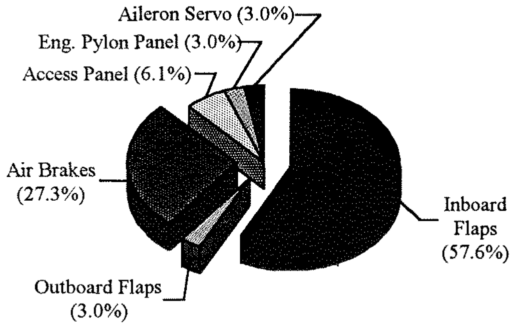


Figure 3 Distribution of Damaged Honeycomb Parts

If in 1994 the cost of a flap aft segment was approximately 3 million Russian Roubles which just allowing for inflation would now cost approximately 18 million Russian Roubles (£2400), however the cost of spare parts has been rising even faster than inflation. The economic justification for an analysis tool which could reduce the replacement rate is therefore strong and growing stronger.

Typical Applications

Although the immediate problem being addressed is that of repair to trailing edge flaps it is realised that the programme should eventually be expanded to cater for a wide variety of honeycomb applications, including fibre reinforced laminated skins and curved shapes.

Typical applications envisaged are:-

- Radomes (Glass Fibre or Kevlar / Nomex)
- Engine Cowlings (Carbon Fibre / Nomex)
- Floors (Glass Fibre / Nomex)
- Furnishings (Glass Fibre / Nomex)
- Aerodynamic Fairings (Glass, Kevlar or Carbon Fibre / Nomex)
- Wing Flaps (Al / Al)
- Spoilers (Al/Al)
- Rudder (Al/Al)
- Elevator (Al/Al)
- Wing Access Panels (Al/Al)

Possible additional applications are:-

- Fuselage Panels (e.g. Raytheon / Beech Starship, Tornado, Jaguar etc.)
- Wing Panels (e.g. Raytheon / Beech Starship)
- Taileron (e.g. Tornado)

Typical Sources of Damage

The principal source of damage varies from one part of the aircraft to another. The major source of damage to trailing edge flaps for example is impact from runway debris whereas for the nose radome it is hail / rain erosion with occasional bird strike.

Other sources of damage could be:-

- Manufacturing error (impact or areas of disbond)
- Maintenance error (impact)
- Lightning Strike
- Static Pitting
- Corrosion

It should be noted that the presence of corrosion in the core is assumed to be a major defect and therefore has not been considered as repairable for the present work.

Russian Airline Practice Related to Damage

To illustrate the current Russian airline practice in dealing with aircraft damage consider the hypothetical case of an aircraft landing at a remote airfield having suffered stone impact damage to a metal honeycomb trailing edge flap.

The first step would be to consult the manufacturer's repair manual which will categorise the damage according to damage area and depth.

Category A:- Minor damage requiring no immediate action.

Category B:- Significant damage requiring standard repair before further flight.

Category C:-Substantial damage requiring the part to be replaced before further flight.

At a remote airfield it is unlikely that there will be the capability of making sophisticated repairs or that the necessary spare parts will be available so that it is likely that damage in Categories B or C will result in the aircraft being taken out of service for a substantial period.

It should be noted that although the standard repair methods described in each Manufacturer's repair manual are generally similar, the theoretical basis for the damage categories varies from one manufacturer to another making direct comparisons difficult.

Typical Repair

Consider a typical repair(3) to a honeycomb panel with damage to one skin and the core (Figure 4).

The repair sequence might be as follows:-

- Drill a circular hole from the damaged side to remove the damaged areas of skin and core but stop short of the undamaged skin.
- Clean out the hole using a vacuum cleaner.
- Prepare a cylinder of honeycomb core to fit into the drilled hole, coat with a non-viscous adhesive and wrap in a synthetic film.
- Apply adhesive to the inside of the undamaged skin at the bottom of the drilled hole.
- Insert the repair core into the hole ensuring good contact with the adhesive on the undamaged skin and use a foaming adhesive to fill the gaps and to bond the repair core to the existing core.

- Remove the excess repair core so that it lies flush with the outer skin line.
- Bond the repair patch over the hole using adhesive.

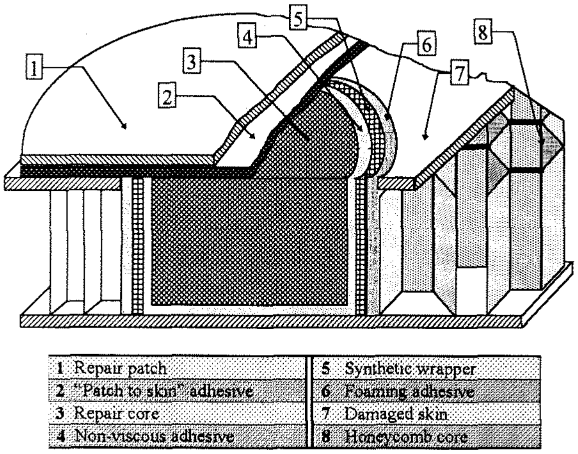


Figure 4 Typical Repair to Honeycomb Panel

Work Description

The work has been split into discrete stages so that the programme can be easily checked at each stage and to ensure that the complexity of the programme is kept to a minimum consistent with achieving it's objectives.

The work described below relates purely to the first stage in the process of the programme development.

First Stage

As the programme has to be able to work effectively whilst making the minimum demand on computer hardware the first stage of the work was to establish a minimum theoretical foundation (4), (5). The advantage of using a very basic theoretical core is that the answers are easily checkable and attention can be concentrated on the input / output options and programme architecture.

Theory

The first problem to be addressed was that of damage to a trailing edge flap and so the following crude simplifying assumptions have been made(6):-

- St Venant's stresses only considered (i.e. no local loading effects).
- Flap is fully fixed (infinitely stiff) continuously along one edge and free on the other three.
- Skin material is isotropic.
- Skins are flat and of equal thickness.
- The problem has been reduced to a 2-dimensional cantilever beam.
- The effect of non-parallel skins has been ignored except for bending section calculations.
- The loading has been assumed to be acting normal to the bottom surface.
- The section has been idealised as a core carrying shear only with zero shear in the skins.
- The repair patch is circular.

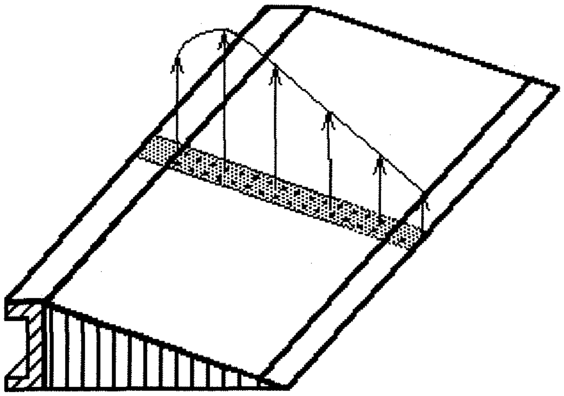


Figure 5 Simplified Flap Model

Figures 5 and 6 shows the 2-dimensional beam which has been assumed taken from the middle of a long flap. The leading edge has been assumed to be fully fixed.

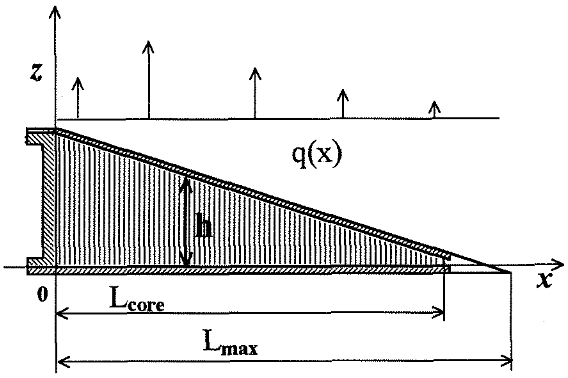


Figure 6 Section Through Flap

Damage Model

For the first stage work the following assumptions regarding the repair, as shown in figure 7,have been made:-

- The repair core has the same properties as the original core.
- The repair patch carries all the direct load from the skin across the damaged area i.e. redistribution of skin load around the damaged area has been ignored.

- The critical mode of failure is shear failure in the patch / skin adhesive(7).

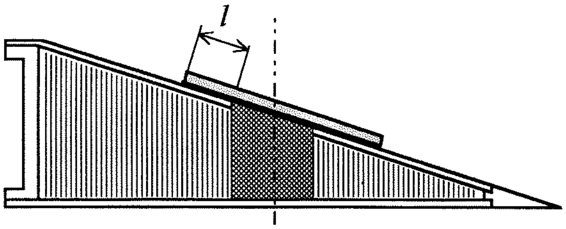


Figure 7 Section Through Repaired Flap

Because at this stage the repair to the core has been assumed to perfectly match the original core it can be ignored and so only the effects of the repair patch, adhesive layer and hole in the skin needed to be addressed(8) (Figure8).

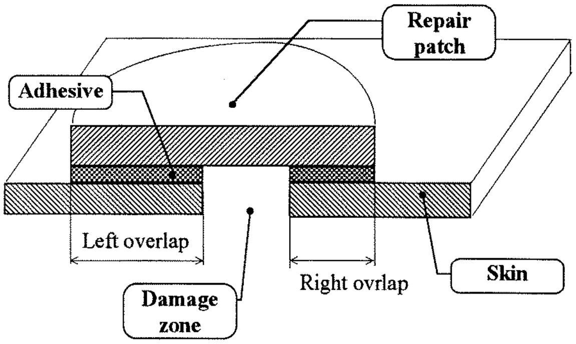


Figure 8 Detail of Top Skin Repair Area

Programme Architecture

In order to design the programme architecture it was necessary to envisage the circumstances in which it will be used. Because the need for this work had been identified by a Russian repair bureau it was obvious that the programme must, as a minimum, meet their needs. It was felt that if the programme were constructed as a series of modules then the needs of a variety of end users could be met without detriment to the programme as a whole so that for example an optimisation module or check stress module could be added if required.

Typical Expected Use of SOTA

Consider the hypothetical case, considered above, of an aircraft landing at a remote airfield having suffered stone impact damage to a metal honeycomb trailing edge flap. The airfield is assumed to be without repair facilities.

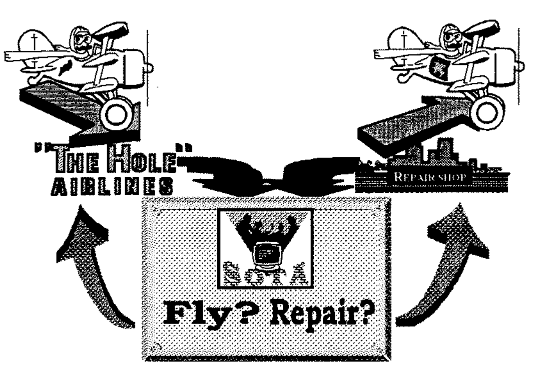


Figure 9 Action Diagram using SOTA

The actions to be taken (Figure 9) are assumed to be:

- The flight engineer will inspect the damage and notify the airline of the details of the damage sustained.
- The airline will consult a repair organisation (either it's own or third party).

The questions which need to be answered are:

1. Can the aircraft be flown safely to a repair organisation in it's present state? If it can are there any restrictions e.g. limitations on weather or weight. If the answer is no then the aircraft will be grounded until it can be repaired in situ.
2. Can the damage be repaired ? If it can then the details of the optimum repair need to be produced by the consultants bearing in mind the materials and techniques available at the repair site.

Macro Algorithm

The programme has been written in modular form so as to be easily adaptable to meet the needs of a variety of users. Figure 10 shows the macro algorithm in diagrammatic form.

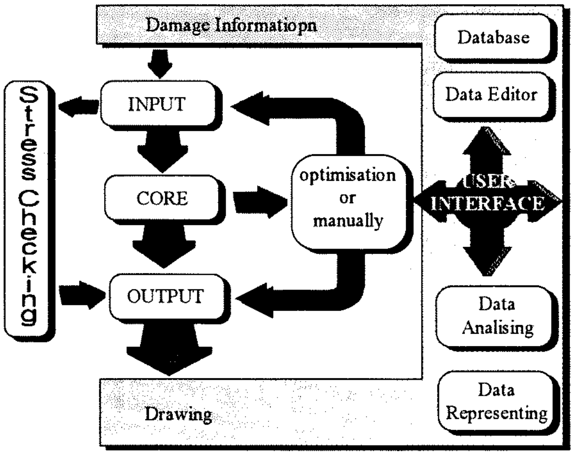


Figure 10 Macro-Algorithm

User Interface

The user interface is the most complex part of the algorithm as this needs to be able to accept input data in a variety of formats and degrees of completeness$^{(9)}$ and present results in a suitable form.

The input data can either be accessed direct from an existing database or supplied manually and stored in a database. In the case of using an optimisation module the results of one iteration will have to be accessed as input data for the next.

The results of the programme operation are stored in database form and are converted into the output format chosen by the user.

The programme therefore needs to have a sophisticated interpreter for communicating between the database editor, data analyser, add-on options and the input and output modules.

Input

The basic minimum requirements for the programme input are the geometric and material characteristics for the undamaged structure as well as the position and dimensions of all the damage sites together with the physical properties of available repair materials. It is strongly recommended that loading information be supplied as well otherwise the programme will design a static full strength repair.

Output

The results can be output in a variety of formats at the discretion of the user.

Example

Consider the example of a two dimensional analysis of a trailing edge flap aft segment with damage as shown in figure 11.

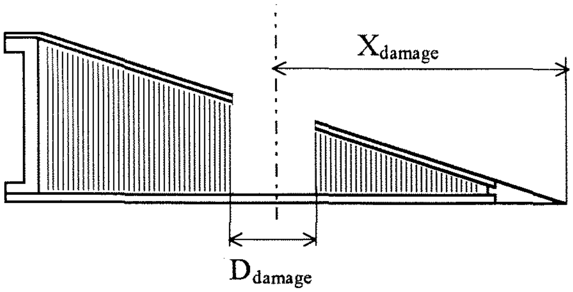
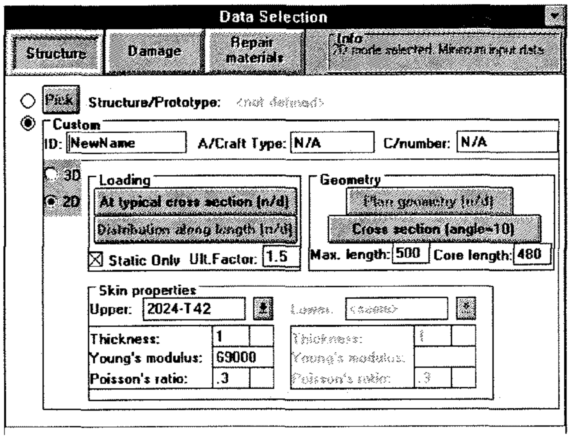


Figure 11 Example of Damaged Flap

- Skin Material :- 2024 - T42
- Skin Thickness :- 1 mm
- Core Material :- 5052
- Core Cell Size :- 6.35 mm ($\frac{1}{4}''$)
- Foil Thickness :- 2.54 x 10^{-2} mm (10^{-3} ")
- Max. damage dimension :- 200 mm
- Distance from the rear edge :- 250 mm
- Uniform Pressure Case :- 0.1 N/mm^2 Ult.
- Adhesive Lap Shear Strength:- 8 N/mm^2 Ult.
- Adhesive Shear Modulus:- 5000 N/mm^2
- Adhesive Thickness:- 0.08 mm

SOTA Input

The input screen for structural data input is shown in figure 12. The first choice is whether to select a structure already in the database or to create customised structural data.



○ Structure/Prototype: <not defined>
● Custom
ID: NewName
A/Craft Type: N/A
C/number: N/A
○ 3D
● 2D
☒ Static Only
Ult.Factor: 1.5
Max. length: 500
Core length: 480
Upper: 2024-T42
Lower: <same>

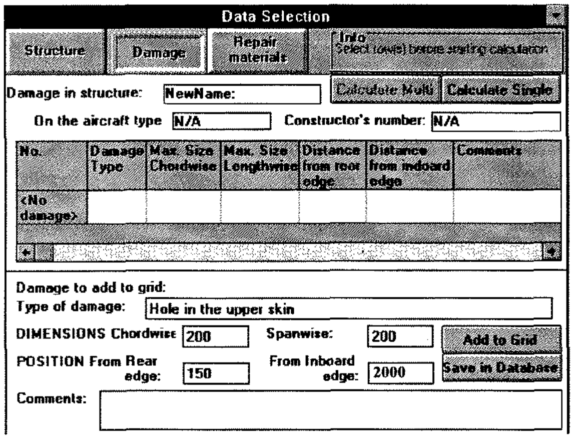
Thickness:	1		Thickness:	1
Young's modulus:	69000		Young's modulus:	
Poisson's ratio:	.3		Poisson's ratio:	.3

Figure 12 SOTA Structure Input Screen

In the example given a new structure called "NewName" has been created for a two-dimensional static analysis. As the analysis is only to be two dimensional the distribution of loading along the length and plan geometry are irrelevant and therefore these buttons are inactive, however, loading and geometric data will have to be given for a typical cross section together with the appropriate ultimate factor.

The skin material has been selected as 1 mm thick 2024-T42 from the materials database and the relevant material properties are displayed. As at this stage in the programme development the skins are assumed to be identical the data box for the lower skin material is inactive.

In later versions of the programme there will be similar boxes for the input of core and core / skin adhesive materials data.



Damage in structure: NewName:

On the aircraft type N/A Constructor's number: N/A

No.	Damage Type	Max. Size Chordwise	Max. Size Lengthwise	Distance from root edge	Distance from inboard edge	Comments
<No damage>						

Damage to add to grid:

Type of damage: Hole in the upper skin

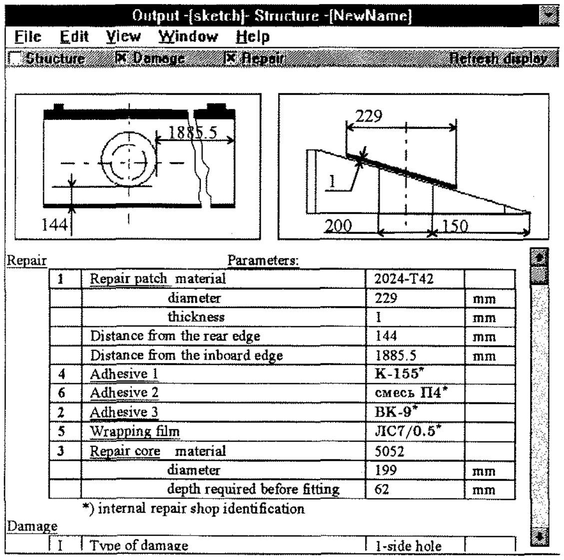
DIMENSIONS Chordwise 200 Spanwise: 200

POSITION From Rear edge: 150 From Inboard edge: 2000

Comments:

Figure 13 SOTA Damage Data Input Screen

The data defining the damage sustained is input via the input screen shown in Figure 13. It should be noted that although in this example there is only one area of damage the programme can evaluate structures with multiple damage sites.



Repair Parameters:

1	Repair patch material	2024-T42	
	diameter	229	mm
	thickness	1	mm
	Distance from the rear edge	144	mm
	Distance from the inboard edge	1885.5	mm
4	Adhesive 1	К-155*	
6	Adhesive 2	смесь П4*	
2	Adhesive 3	ВК-9*	
5	Wrapping film	ЛС7/0.5*	
3	Repair core material	5052	
	diameter	199	mm
	depth required before fitting	62	mm

*) internal repair shop identification

Damage

I	Type of damage	1-side hole	

Figure 14 SOTA Results Screen

All the parameters required to draw engineering repair drawings will be presented on the results screen, an example of which is shown in figure 14. The graphic presentation is multilayered so that the user can select which dimensions to display. The numbers in the first column refer to those shown in figure 4 which also forms part of the help file available for the results screen. The user can also access a further screen which can access an optional module which contains details of company standard procedures. The form of this screen would be dependant on the user but could either include all the relevant information from the company repair procedures or could just refer to the appropriate documentation.

It should be noted that the results screen shown in figure 14 relates to a circular repair patch defined using a two dimensional analysis. The problem of displaying a repair patch of non-standard shape, derived from a three dimensional analysis, so that it can be positioned and oriented accurately in a practical repair situation is currently being addressed. If a specific aircraft part has been selected then the repair data will be added to it's part history database.

Figure 15 shows the repair for the example which would have been declared as scrap using the present standard methods.

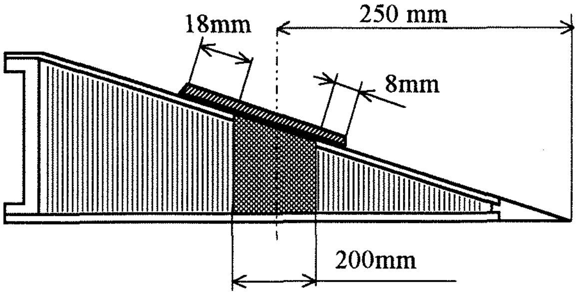


Figure 15 Section through Repair

Conclusions

The programme as it exists at the moment is deliberately very restricted in it's application to allow effort to be concentrated on the input / output phases in the macro algorithm and to ensure that the additional complexities in the programme brought about by refinement of the theory are justified for practical situations.

Future Improvements

The handling of input and output data is constantly under review and will progressively be improved.

The main planned improvements are concerned with expanding the theoretical base to allow the analysis of a variety of practical problems.

The first improvements to be considered are three dimensional modelling, non-circular repair patches, varying edge support conditions and inclusion of local attachment effects.

Eventually it is hoped to expand the scope of the programme to cater for fibre reinforced skin materials and a variety of core materials e.g. nomex honeycomb, syntactic foam etc.. and also to predict fatigue safe lives for the repaired structures.

Validation

The programme will develop in a series of steps with the each step being checked against a set of examples to ensure that the results agree with theory. In the later stages of development it is planned to perform a restricted number of physical tests and to model these using a finite element package. Once the finite element models accurately represent the test situation then a large number of additional cases will be analysed using the finite element method and compared with the results from SOTA.

Acknowledgement

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