University of Nottingham
School of Mechanical, Materials, Manufacturing Engineering & Management

Project:	**FENET EU Thematic Network** (Contract G1RT-CT-2001-05034)
Report Title:	**Post-Workshop Report on Durability & Life Extension** **FENET Workshop - DLE-01** **Finite Element Simulation of Contact Problems –1** **(27-28 February 2002, Copenhagen)**
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1. Introduction

This was the first FENET workshop on issues related to Durability and Life Extension. The workshop was concerned with contact problems, including impact, friction, sliding and case studies. The seminar addressed the following issues:

- FE contact benchmarks
- Difficulties experienced by FE users in modelling contact problems
- Current limitations of commercial FE software
- Desirable contact features that are not currently offered by FE software.
- The need for further research in the application of FE to contact problems

2. Contact Workshop Objectives

The main objectives of the contact workshop are:

- To present and review the existing set of contact benchmarks
- To obtain feedback from FE users on the contact benchmarks
- To identify more challenging contact benchmarks
- To identify limitations in the contact capabilities of commercial FE software
- To identify future desirable features in contact simulation using FE
- To present cases studies reflecting modern FE contact analysis

3. List of Presentations

Day 1 - Wednesday 27 February 2002

Presentation	Speaker
Workshop introduction and objectives	Prof. Adib Becker (University of Nottingham, UK)
Finite Element Modelling of contact phenomena in structural analysis (Keynote lecture)	Albert Konter (Netherlands Institute for Metals Research, Netherlands)
Overview of current NAFEMS contact benchmarks (Keynote lecture)	Dr. Nawal Prinja (NNC, Limited, UK)
Evaluation of the current contact benchmarks by software vendors and FE users	Adrie Bout (MSC Software Benelux B.V., Netherlands) Dr.-Ing. Reinhard Helfrich (INTES, Germany) David Ellis (IDAC, UK)
More challenging contact benchmarks	Dr. Alan Prior (HKS (UK) Limited)
Coupling FE contact and heat transfer analysis in investment casting simulations	Gottfried Laschet and L. Haas (Access e.V., Germany)

Solving contact problems using an augmented Lagrangian method	Dr. Philippe Jetteur (Samtech, Belgium)
Alternative Technology: Boundary Element Contact Analysis	Prof. Adib Becker (University of Nottingham, UK)
Paper Calendering: FE Simulation As an Optimisation Tool	Dr Yasar Deger (Sulzer Markets & Technology Ltd, Switzerland)
Discussion and Overview of FENET Workshops on Durability and Life Extension	Prof. Adib Becker (University of Nottingham, UK)

Day 2 - Thursday 28 February 2002

Presentation	Speaker
Contact Workshop Conclusions/ Discussion Forum	Prof. Adib Becker (University of Nottingham, UK)

4. Analysis of Contact workshop

Comments from the workshop participants are listed below.

(i) Comments on the current NAFEMS contact benchmarks

- Limited in scope, but important as the first step in establishing contact benchmarks
- Limited to 2D contact only
- Limited to continuum elements
- Can be improved by a clearer definition of data input
- Would benefit from showing solutions from two or more FE codes
- Useful to add a detailed "educational" description of the 'difficult' benchmarks.
- Should also consider the curved patch test
- Should show all FE mesh details (all nodal coordinates)

(ii) More challenging contact benchmarks

- 3D contact
- Self-contact
- Multi-body contact
- Stick-slip in contact area
- Rotating shaft with no friction
- Compression of rubber
- Shell on shell contact
- Beam contact
- Explicit/Implicit comparison
- 2D/3D Linear vs. quadratic elements
- 3D tetrahedron vs. hex elements

- 3D 27 node brick elements
- Impact (high velocity)
- Dynamic contact (low velocity)
- Large strain contact
- Metal forming

(iii) Challenges in FE modelling of industrial contact problems

- Loaded rigid surfaces
- Identification of unknown or unexpected contact regions
- Automation of contact analysis
- Re-meshing during contact analysis
- Visualisation of contact elements
- Informative post-processing diagnostic display
- Improved quadratic elements
- Better friction models
- Experimental verification of FE contact solutions
- Coupled thermo-mechanical contact
- Heat conduction across interfaces
- Cemented joints
- Thin lubricating films

5. Concluding Remarks

The contact workshop has been successful in stimulating many discussions regarding the need for further contact benchmarks and case studies. It was acknowledged that although the current published NAFEMS benchmarks are limited in scope, they are important as the first step in establishing contact benchmarks.

Most delegates agreed that there is genuine need for more complex contact benchmarks. This will be addressed by Non-linear working Group of NAFEMS with a view to commissioning further benchmarks and launching further contact workshops. Additionally, discussions will also be held with NAFEMS regarding responding to the queries raised about the current published contact benchmarks.

In view of the interest generated by this workshop, a second FENET workshop will be planned for the Durability and Life Extension series of workshops. The objectives of the second workshop will be to define a new set of more advanced benchmarks and to invite feedback from FE analysts.

Appendix A
Summaries of Contact Workshop Presentations

Finite Element Modelling of contact phenomena in structural analysis
Albert Konter, Netherlands Institute for Metals Research, Netherlands

An overview of contact analysis using FE is presented with contact comparisons of two software codes; MSC.MARC and ABAQUS. The topics covered include FE contact benchmarks, difficulties encountered by FE users in modelling contact problems, current limitations of commercial FE codes, desirable contact features not currently offered by FE software, and the need for further research in the application of contact problems.

Overview of current NAFEMS contact benchmarks
Dr Nawal K Prinja, NNC Limited, UK

A brief background is presented to the previous work done by NAFEMS which lead to the development of the latest benchmarks for contact, gapping and sliding problems. The purpose of these benchmarks, classification of the contact problems and how they are reflected in the selected problems are discussed along with full descriptions of each of the ten contact benchmarks. Lessons learnt from the feedback received so far on these benchmarks are discussed.

Contact Benchmarks with MARC
Adrie Bout, MSC Software Benelux, The Netherlands

Contact benchmark results obtained with MSC.Marc are presented. The differences between the results and those published in the NAFEMS report are discussed. Some potential improvements in the benchmark descriptions are discussed.

Contact Benchmarks with PERMAS
Dr.-Ing. Reinhard Helfrich

A number of benchmarks out of NAFEMS Report R0081 together with the results achieved by PERMAS are presented (CGS-1, CGS-2, CGS-3) are presented. In addition, a number of benchmark cases are proposed to cover frictional contact. Finally, some general comments on contact analysis are discussed.

More challenging contact benchmarks
Dr Alan Prior, Hibbitt, Karlsson & Sorensen (UK) Ltd, UK

The existing contact benchmarks have made an excellent start in examining the various issues associated with contact analysis in FE. However, the scope of the benchmarks is, of necessity, limited. In this talk some proposals for future benchmarks are considered, looking at the industrial requirements and state of the art in contact modelling, within the framework of NAFEMS benchmarks.

Coupling FE contact and heat transfer analysis in investment casting simulations
G. Laschet and L. Haas, Access e.V., Germany

Accurate prediction of solidification response is a key factor in the numerical simulation of casting processes. An important aspect of investment casting simulation is the calculation of heat transfer between mould and casting during the solidification process. This analysis requires coupling between the temperature and stress/strain simulation in order to determine a gap formation, which crucially impacts on heat transfer between mould and metal. The presented model is based on a frictionless 3-D contact algorithm of master-slave type. Its main advantage is the more accurate evaluation of the heat transfer in the mould/metal gap. The accuracy of the developed contact algorithm is illustrated on Crisfield's contact benchmark test. Results for the solidification of a dummy blade as well as a new benchmark problem for coupled thermo-mechanical contact analysis are presented. This benchmark is related to the accurate prediction of the dimensional stability of a thin 3-D aeronautical segment produced by investment casting.

Solving contact problems using an augmented Lagrangian method
Dr. Philippe Jetteur, Samtech, Belgium

This presentation deals with contact in non-linear analysis with implicit schemes. In order to solve the contact problem, an augmented lagrangian procedure is used. The resulting system of equations is solved simultaneously for the displacements and Lagrange multipliers. Special care is taken when the flexible body is modelled by second order elements.

Alternative Technology: Boundary Element Contact Analysis
Prof. Adib Becker (University of Nottingham, UK)

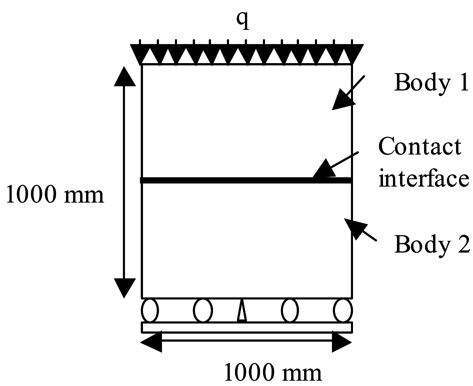
This presentation is concerned with the development of 3D frictional contact benchmarks using a Boundary Element formulation. The contact variables are defined with respect to each of the surfaces using local co-ordinate systems. Equilibrium conditions, displacement continuity requirements, and Coulomb's law of friction applied to 3D contact are used to derive the contact equations. These equations are directly coupled at the contact interface to form a reduced set of determinate simultaneous equations. A number of 3D frictional contact applications covering stationary and advancing contact surfaces are presented in which boundary element solutions are compared to the corresponding finite element solutions. Results are presented in the form of normal contact stresses, shear stresses and relative tangential displacements, and the stick/slip partitioning of the contact interface.

Paper Calendering: FE Simulation As An Optimisation Tool
Dr Yasar Deger, Sulzer Markets & Technology Ltd, Switzerland

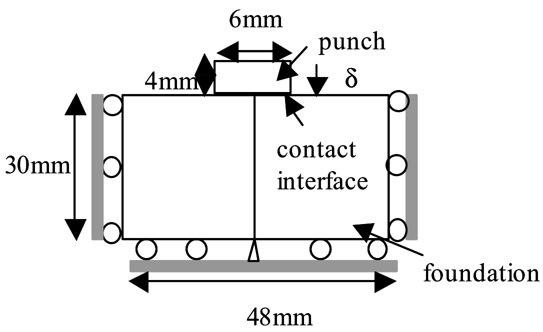
In the production process, paper is calendered (smoothed) under high temperature and pressure whilst passing through one or more nips formed by elastic and hard rolls at high speeds. The quality of the paper is dependent on various operational parameters, including the positioning and interaction of the rolls. Under the contract of VSPT (Voith Sulzer Finishing GmbH, Krefeld, Germany) Sulzer Innotec has performed an investigation of the deformations of the individual rolls and their contact properties under selected operational conditions for two different positions of the calender. The work aimed firstly to prove qualitatively that the model reproduces the deformation and force quantities observed during operation of the present calender. In a second step, changes of the significant contact pressure distributions and deformations of the rolls were to be estimated for a prospective modification of the roll positions. In addition, the influence of the rolling movement on the contact conditions has been studied by means of the "steady state transport" analysis capability of ABAQUS. This method suitably combines the Eulerian and Lagrangian approaches for the description of movement and deformation and accounts for frictional and inertial effects. Selected modelling details and results were presented.

Appendix B
The Published NAFEMS Contact Benchmarks

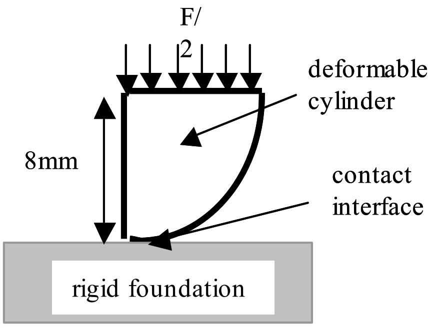
The following contact benchmarks have been published by NAFEMS in 2001. *(Ref: Feng, Q. and Prinja, N.K. "Benchmark tests for FE modelling of contact, gapping and sliding", NAFEMS Report R0081, 2001).*



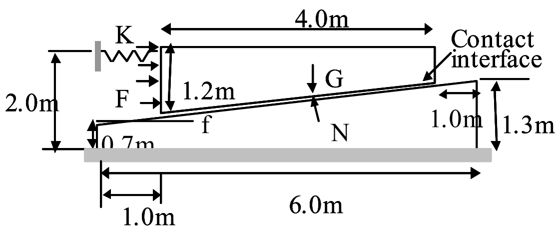
CGS-1: Contact patch test



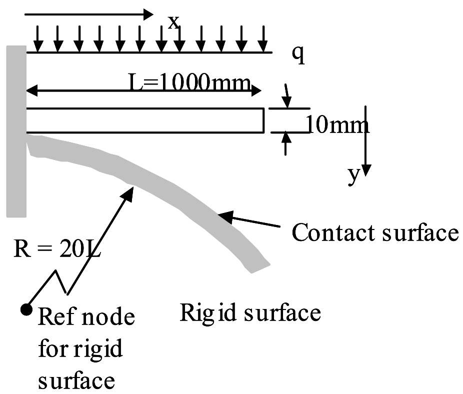
CGS-2: Rigid punch on a deformable foundation



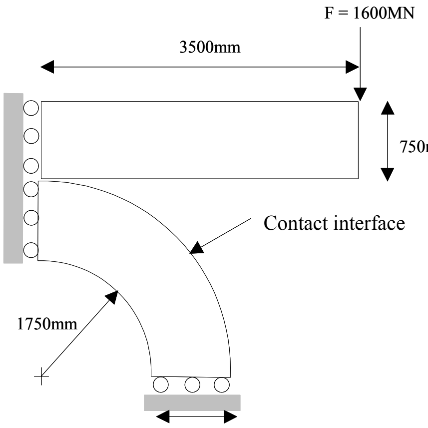
CGS-3: Hertzian contact



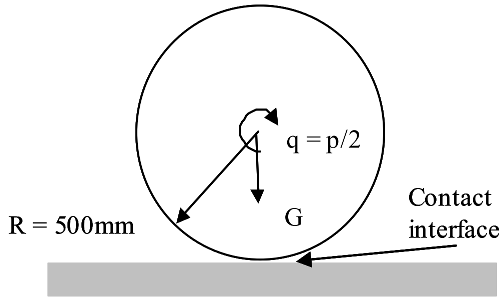
CGS – 4: Sliding wedge



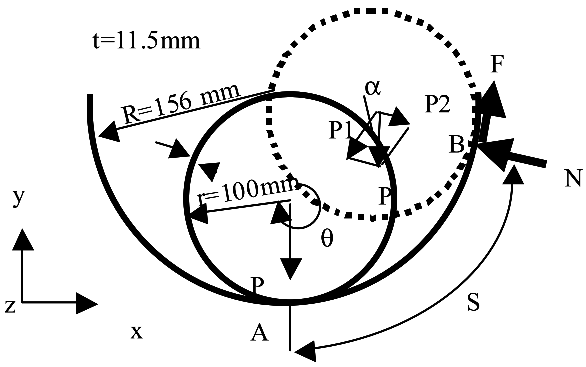
CGS – 5: Cantilever beam loaded against a rigid curvilinear surface



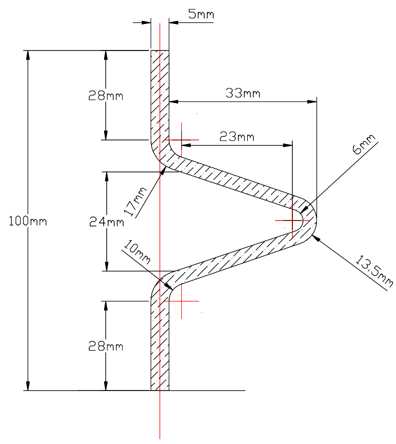
CG-6 Bending of a plate over a stiff cylinder



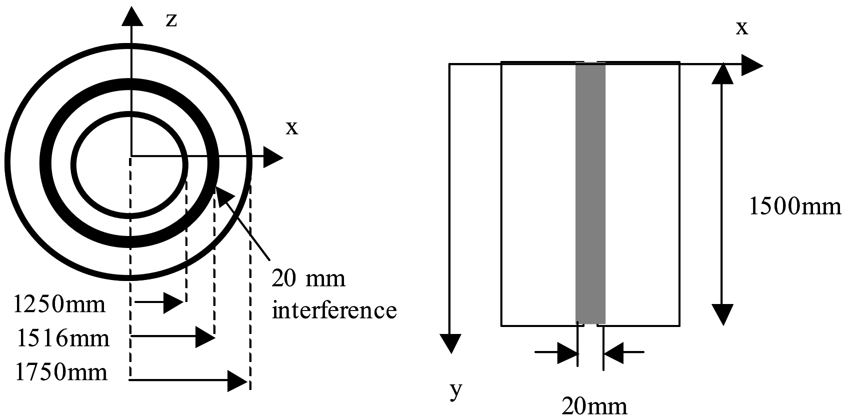
CGS – 7: Sliding and rolling of a ring on a rigid surface



CG8: Two contacting rings



CGS – 9: Buckling of a curved column with self-contact



CGS – 10: Interference between two cylinders

Appendix C
Feedback Comments on the Published NAFEMS Contact Benchmarks

The following comments were received on 26 March 2002 from Dr. N. Prinja (NNC Ltd., UK) concerning the queries from participants regarding the published NAFEMS contact benchmarks report.

<u>CGS - 1: Contact patch test</u>

- Try linear and quadratic elements and clarify their use in the report.
- Supply exact definition of nodal coordinates.
- Perform the analysis over only one increment.
- Do not use node numbers for displaying the results.
- Define which side of the contact interface is used to display the contact pressures.

<u>CGS - 2: Rigid punch on deformable foundation</u>

- Clarify the Boundary Conditions at the edge of the foundation.
- Explain why the rigid punch is meshed.
- Explain why a singularity is modelled.
- The results will be sensitive to the mesh density.

<u>CGS - 3: Hertzian contact</u>

- Half cylinder rather than the quarter cylinder should be used for direct comparison with the Hertz solution.
- Note that the loaded surface in the quarter model does not remain horizontal.
- Try linear as well as quadratic elements.

<u>CGS - 4: Sliding wedge with linear springs</u>

- Explain how the 'G' load is applied.
- Clarify the exact position of the springs.

<u>CGS - 5: Cantilevered beam loaded against a rigid curvilinear surface</u>

- Check the reference solution.
- Assumed Strain Formulation may give better results.
- The equation presented in the report does not give the quoted results.

<u>CGS - 6: Bending of a plate over a stiff cylinder</u>

- Specify whether the point load is a follower load.
- Specify whether the reference solution uses linear or quadratic elements.
- The contact pressure distribution is not given in the quoted reference.

<u>CGS - 7: Sliding and rolling of a ring on a rigid surface</u>

- Model the flat surface as a softer material and observe the change in the x-displacement.

<u>CGS - 8: Two contacting rings</u>

- No comments.

<u>CGS - 9: Buckling of a curved column with self-contact</u>

- The geometry of the bent column is not clear. Nodal coordinates should be provided.

<u>CGS - 10: Interference between two cylinders</u>

- No comments.

<u>Other General Comments:</u>

- Mention the convergence criteria used to obtain the solutions.
- Include results from more FE codes.
- Provide nodal coordinates and element connectivity data for ease of mesh generation.