Annual Report 2009

Centre for
Research-based
Innovation

Established by the Research Council of Norway

SIMLab

Centre for Research-based Innovation

SINTEF

NTNU – Trondheim
Norwegian University of
Science and Technology

Vision

Our vision is to establish SIMLab as a world-leading research centre for the design of **Crashworthy and Protective Structures**

Objective

Within the field of structural impact SIMLab is concentrating on research areas that are of common interest to its industrial partners and hence create a link between Norwegian industry and some of the major actors in the global market, i.e. the automotive industry. However, in order to meet the requirement for innovation and value creation in an international market, Norwegian industry has to adopt new and original knowledge in product development. Here, an efficient modelling of the whole process chain, throughprocess modelling, is a key requirement for success where a strong coupling is made between materials, product forms, production process and the structural behaviour. In order to meet the future challenges in product development foreseen by these partners, a multidisciplinary approach is used where researchers from the partners and academia contribute. This is only achievable through activities at the Centre with long-term objectives and funding. Thus, the main objective of the Centre is

to provide a ***technology platform*** *for the development of safe and cost effective structures*

Goals

The main quantitative goals of the Centre are as follows:

- **Industrial: 1)** To implement the developed technology by mutual exchange of personnel between the Centre and the industrial partners. **2)** To arrange annual courses for these partners. **3)** To facilitate employment of MSc and PhD candidates at the industrial partners.
- **Academic: 1)** To graduate 10 PhD candidates where at least three are female. **2)** To graduate 10 MSc students annually. **3)** To attract 5 international professors/scientists during the duration of the Centre. **4)** To publish on average 8 papers annually in international journals with peer review in addition to conference papers. **5)** To arrange two international conferences.

Industrial partners

HYDRO · Statens vegvesen · SSAB Swedish Steel · Audi · Renault · Statoil · Forsvarsbygg

Summary

SIMLab (Structural Impact Laboratory)- Centre for Research-based Innovation - is hosted by Department of Structural Engineering, Norwegian University of Science and Technology (NTNU) in cooperation with Department of Materials Technology, NTNU and SINTEF Materials and Chemistry.

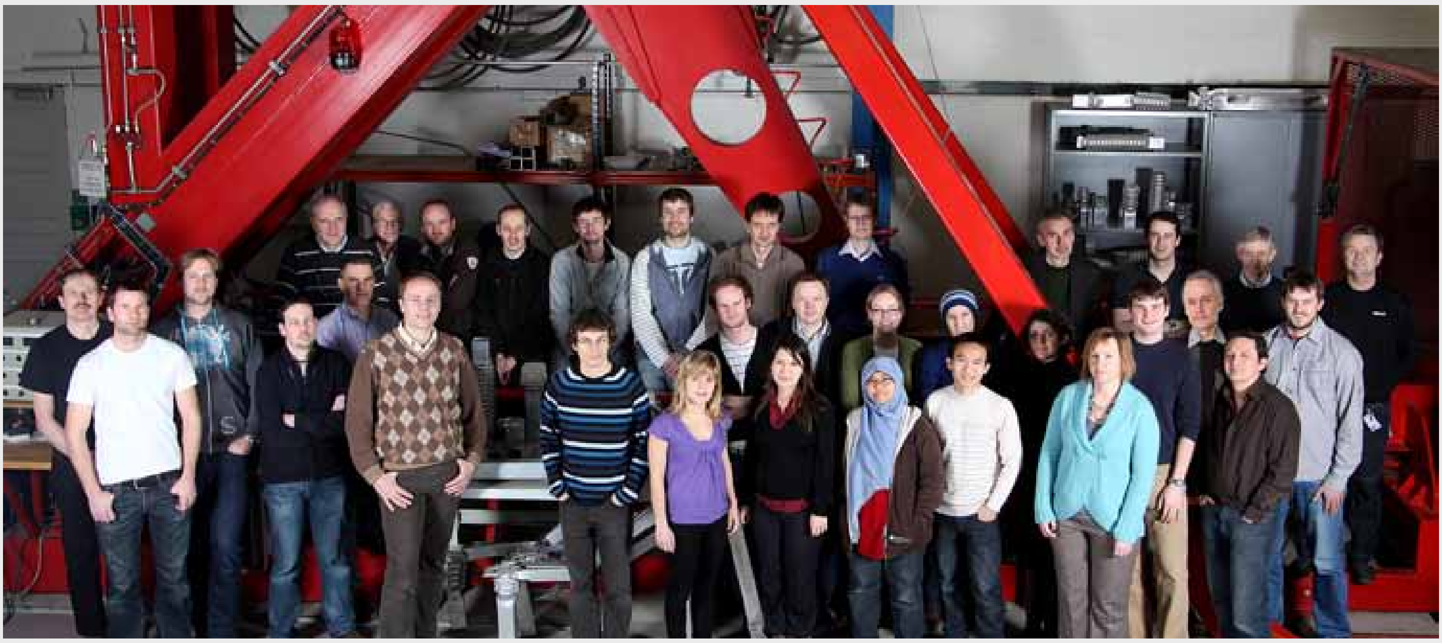
The main objective of the Centre is to develop a technology platform for safe and cost-effective structures in aluminium, high-strength steels and polymers through advances in the research areas *Materials, Solution techniques* and *Structures*. The ability of lightweight structures to withstand loads from collisions and explosions is a key issue in the Centre. Accurate, robust and reliable numerical modelling of materials and structures under static and dynamic loading conditions are key issues. Examples of applications are safety innovations in the automotive and offshore industry, improved highway safety as well as protective structures for international peacekeeping operations.

The industrial partners in the Centre in 2009 were Hydro Aluminium, Audi AG, Renault, Statoil, SSAB Swedish Steel, the Norwegian Public Roads Administration and the Norwegian Defence Estates Agency. BMW and Plastal withdrew from the Centre from January 2009.

The defined research areas are linked with research programmes with focus on *Fracture and Crack Propagation, Connectors and Joints, Polymers, Multi-scale Modelling of Metallic Materials* and *Optimal Energy Absorption and Protection.* For each research programme annual work plans are defined with contribution from PhD candidates, post docs and scientists from the partners in addition to the permanent staff at NTNU. In order to strengthen the cooperation and interaction between the partners seminars and telephone meetings have been held. The latter have been very important due to travel restrictions at the automotive partners. The annual SIMLab seminar was this year hosted by Audi in Neckarsulm 2-4 November 2009. The seminar gathered around 40 participants from all partners and was an excellent arena for fruitful discussions and feedback to the research team on the work carried out during the first three years of the Centre.

The overall management structure of the Centre consists of a board comprising members from the consortium participants. A Centre Director is in charge of the operation of the Centre, assisted by a core team which together with the research programme heads run the research in the Centre. Furthermore, a Scientific Advisory Board of international experts provide scientific and strategic advice based on a defined mandate. The Scientific Advisory Board meeting this year was held in Neckarsulm in November just after the SIMLab seminar. Thus the board members were present during the two-day seminar and got an overview of the work carried out the three first years of the Centre. In their report the board concluded that the Centre has a strong identity which is characterised by its successful integration of theoretical developments and laboratory investigations into finely focused studies. The board noted that the Centre has achieved excellent cooperation with the partners who recognize the uniqueness of this research group.

In 2009 the research work in the Centre has resulted in 31 papers published in peer reviewed journals. Furthermore, 21



The research group. Photo: Melinda Gaal.

papers have been published in conference proceedings, while 3 keynote lectures at conferences have been given by the research team members.

The research in the Centre is carried out by close cooperation between master's, PhD candidates, post docs and scientists. In 2009 seventeen male master's students, nine male and four female PhD candidates and one female and one male post doc have been connected with the Centre. Five international students have stayed at the Centre for shorter and longer periods during the year.

International cooperation and visibility are success parameters for our Centre. Thus we have had cooperation (with common publications) with the following universities/ research laboratories in 2009: Ecole Normale Supérieure de Cachan/Laboratoire de Mécanique et Technologie (ENS/LMT) and University of Savoie, France; University of São Paulo, Brazil; MIT, USA; University of Linköping, Sweden; Politecnico di Milano and DYNALAB, Italy and Dr M. Forrestal and Dr T. Warren (US companies). In addition the Centre is involved in the Multi-disciplinary University Research Initiative Project (MURI) titled *An Integrated Cellular Materials Approach to Force Protection* which is sponsored by the US Navy. The partners are The University of California Santa Barbara (UCSB) in cooperation with Harvard University, University of Virginia, MIT, all in the USA, and University of Cambridge, UK.

With respect to visibility the activities in the Centre have been presented in international and national newspapers and magazines.

Several concurrent research projects have been run in parallel with the Centre's activities. Furthermore, the Centre has been involved in three EU applications/ initatives.

Research areas

The technology platform is developed through advances in the following basic research areas:

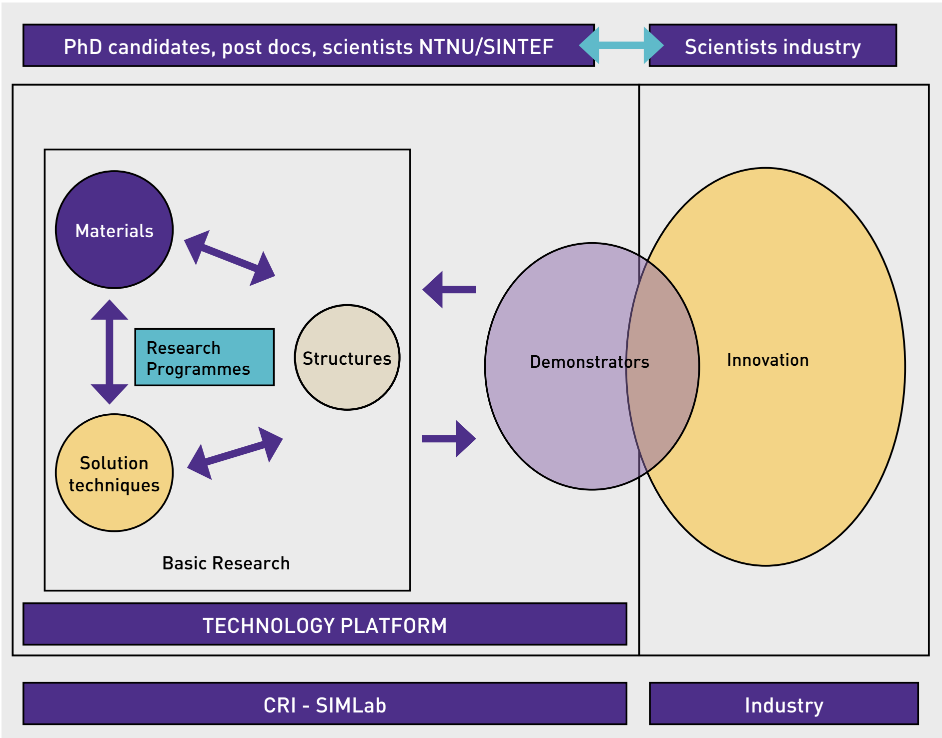
- **Materials:** Development of improved quantitative constitutive models and failure criteria for large-scale analyses as well as identification methods
- **Solution techniques:** Establishment of accurate and robust solution techniques for the simulation of impact problems
- **Structures:** Investigation of fundamental response mechanisms of generic components and structures as well as the behaviour and modelling of joints.

This research area 'Structures' is serving as a link between 'Materials', 'Solution techniques' and the "Demonstrators" activity, see figure below. The selection of demonstrators is carried out in close cooperation with the industrial partners. The interaction between the activities denoted 'Basic Research' and 'Demonstrators' is crucial with respect to validation and possible refinement of the technology developed at the Centre. The Centre is dealing with aluminium extrusions and plates, aluminium castings, high-strength steels and polymers.

Research areas

The basic research areas **Materials, Solution techniques** and **Structures** are linked by **Research programmes**. The number of research programmes and the content in each programme (research projects) can vary dependent on the interest of the partners. The following research programmes have been running in 2009:

- **Fracture and Crack Propagation (F&CP):** Validated models for fracture and crack propagation in ductile materials including rolled and extruded aluminium alloys, high-strength steels, cast aluminium and polymers will be developed. Formulations for shell structures and solid bodies are established for verification and validation. Accuracy, robustness and efficiency are considered to be the major success criteria.



Research areas

- **Optimal Energy Absorption and Protection (OptiPro):** A basis for the design of safer, more cost effective and more lightweight protective structures for both civilian and military applications subjected to impact and blast loading are developed. This also includes road restraint systems as well as submerged pipelines subjected to impact from fishing gear.

- **Polymers (Poly):** Development of validated models for polymers subjected to quasi-static and impact loading conditions. An important prerequisite is to establish a set of test methods for material characterization and to generate a database for validation tests. The programme is for the time being limited to thermoplastics.

- **Multi-scale Modelling of Metallic Materials (M4):** Phenomenological constitutive models of metals are available in commercial FE codes, but they do not provide any information about the physical mechanisms responsible for the observed material response. Thus, in this programme the material response is described on the basis of the elementary mechanisms governing the macroscopically observed phenomena. This approach is required for the design of optimized process chains, for the development of next-generation phenomenological models, and for reducing material characterization costs.

- **Connectors and Joints (C&J):** Information about the behaviour and modelling of self-piercing rivet connections subjected to static and dynamic loading conditions are obtained. Special focus is placed on the establishment of a model to be used for large-scale shell analyses as well as the behaviour of joints using dissimilar materials.

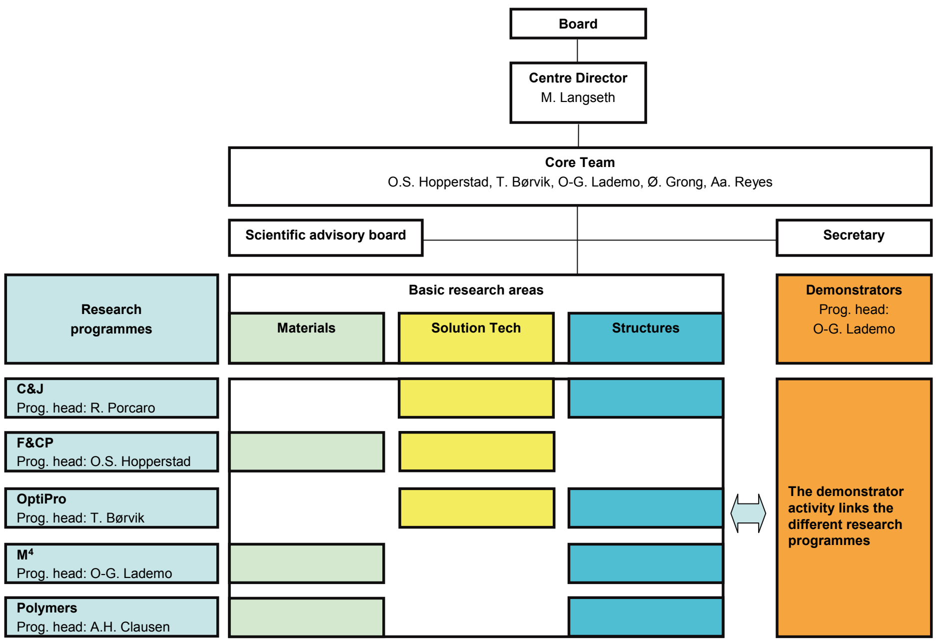
Research organization

Structure of organization

The overall management structure of the Centre consists of a board comprising members from the consortium participants. The Centre Director is in charge of the operation of the Centre, assisted by a core team and the research programme heads. Within each research programme, research projects are defined with a project leader. Furthermore, an advisory scientific board of international experts provides scientific and strategic advice.

The Board

- Karl Vincent Høiseth, Professor/ Department Head, Department of Structural Engineering, NTNU (Chairman from August 2009)
- Svein Remseth, Professor/Department Head, Department of Structural Engineering, NTNU (Chairman until August 2009)
- Thomas Hambrecht, Head of Functional Design, MLB, Audi AG
- Torstein Haarberg, Executive Vice President, Sintef Materials and Chemistry
- Håvar Ilstad, Principle Researcher, Statoil
- Helge Jansen, Senior Vice President, Hydro Aluminium
- Helge Langberg, Head of Research Department, Norwegian Defence Estates Agency
- Per Kr Larsen, Professor, Department of Structural Engineering, NTNU
- Joachim Larsson, Manager, Knowledge Service Center/Design, SSAB Tunnplåt AB
- Eric Vaillant, Engineering Department Manager, Renault
- Sigurd Olav Olsen, Director of Transport Supervision Section, Norwegian Public Roads Administration
- Ingvald Strømmen, Professor/Dean, Faculty of Engineering Science and Technology, NTNU



Structure of organization in 2009.

Centre Director

- Magnus Langseth, Professor, Department of Structural Engineering, NTNU

Core team, programme heads and secretary

- Tore Børvik*, Dr. ing., Norwegian Defence Estates Agency
- Arild Holm Clausen, Professor, Department of Structural Engineering, NTNU
- Øystein Grong, Professor, Department of Materials Technology
- Arve Grønsund Hanssen*, Dr. ing., Impetus Afea AS (from November 2009)
- Odd Sture Hopperstad, Professor, Department of Structural Engineering, NTNU
- Odd-Geir Lademo*, Dr. ing., SINTEF Materials and Chemistry
- Raffaele Porcaro, PhD, SINTEF Materials and Chemistry (until November 2009)
- Aase Reyes, Assoc. Professor, Department of Structural Engineering, NTNU
- Mona Bakken, Secretary

** Adjunct Professor at Department of Structural Engineering (20% position)*

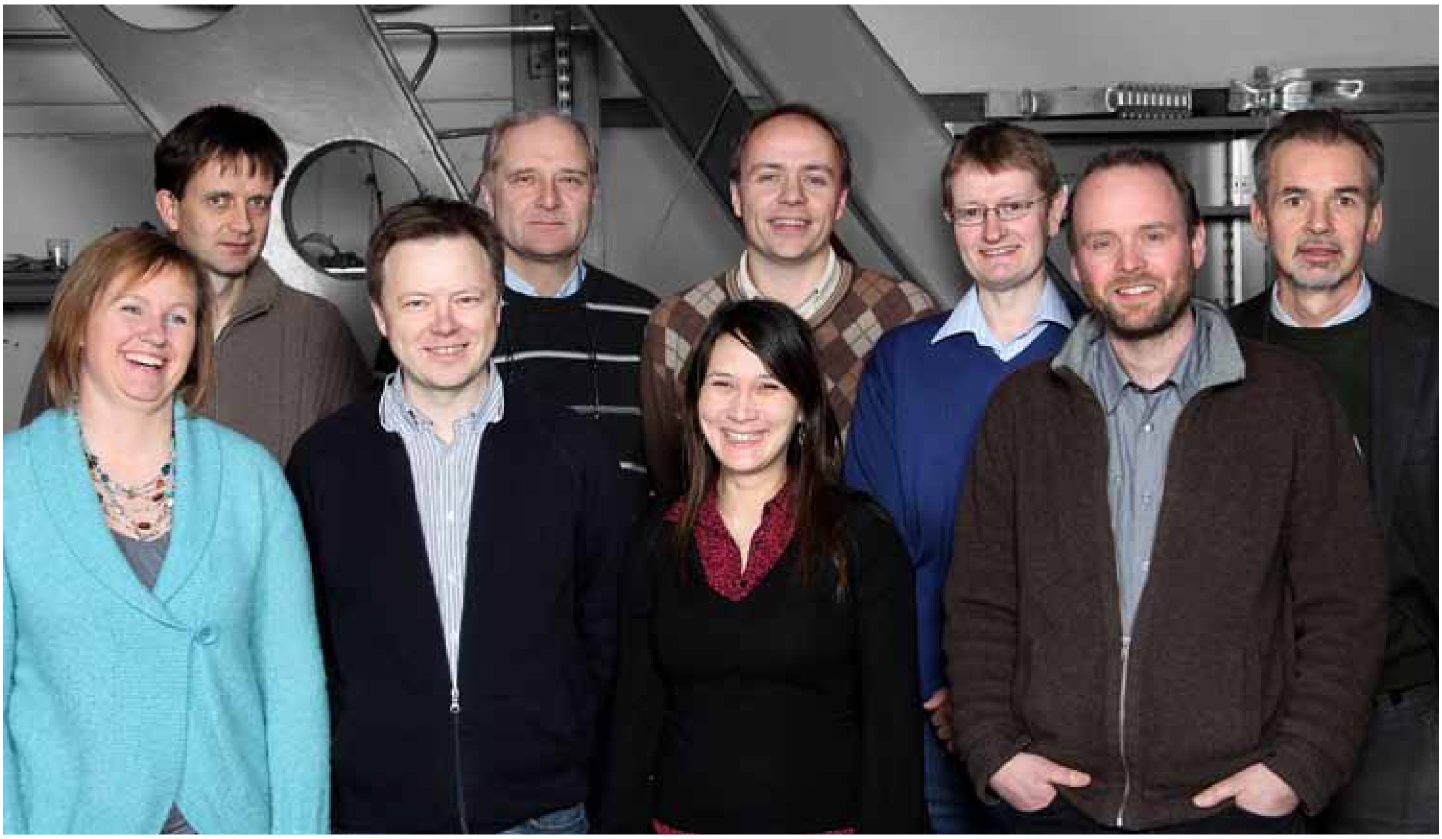
Scientific Advisory Board

- Professor Ahmed Benallal, LMT-Cachan, France
- Professor Emeritus David Embury, MacMaster University, Canada
- Professor John Hutchinson, Harvard University, USA
- Professor Emeritus Norman Jones, University of Liverpool, UK
- Professor Larsgunnar Nilsson, University of Linköping, Sweden
- Professor Klaus Thoma, Ernst Mach Institute, Germany

Partners

- Host institution
  - NTNU
- Research partner
  - SINTEF Materials and Chemistry
- Industrial partners
  - Audi AG
  - Hydro Aluminium
  - Renault
  - SSAB Swedish Steel
  - Statoil
  - The Norwegian Public Roads Administration (NPRA)
  - The Norwegian Defence Estates Agency (NDEA)

Plastal and BMW withdrew from the Centre from January 2009.



From left: Mona Bakken, Arild H. Clausen, Tore Børvik, Magnus Langseth, Aase Reyes, Odd-Geir Lademo, Odd Sture Hopperstad, Arve Grønsund Hanssen and Øystein Grong.

Photo: Melinda Gaal.

Cooperation and interaction between partners

The annual work plans for each programme were defined with contributions from each partner. NTNU and SINTEF scientists, PhD candidates and post docs have been the main contributors to perform the work, while each industrial and public sector partner has participated based on their defined contribution-in-kind. The contributions-in-kind for NPRA, Audi and Renault are mainly taken care of by PhD candidates spending half time at the Centre and half the time at the respective industrial partner. Furthermore, NDEA has a scientist who is permanently working at the Centre with good contact with the NDEA research and development group in Oslo. The cooperation and spread of information within the main research group (NTNU and SINTEF) and between the industrial partners are carried out using programme and project meetings as well as seminars.

Programme and project meetings: Once a week the Centre Director had a meeting with the programme heads and the core team members. These meetings were used to coordinate the activities in the research programmes and to ensure that the progress and cost plan as well as the deliverables were in accordance with the defined annual work-plans. In addition, specific project meetings were held within each research programme when necessary with participation from all involved partners. These project meetings were supported by telephone meetings with our international partners 1-3 times a year. In order to strengthen the spread of information within the Centre an internal seminar was held every second week including a short presentation of a research topic by one of the Centre members (professors, scientists, PhD candidates and post docs).

Seminar November 2009: A seminar with participation from all partners was hosted by Audi in Neckarsulm 2-4 November 2009. The seminar started with a guided tour at the Audi A6 production line followed the next two days by presentations and discussions. The technical presentations were opened by the Centre Director, who gave an overview of the Centre objectives and strategies as well as a summary of the obtained results after three years. The content in each research programme was presented and linked to material models and technology under development to be used by the partners in their process and product development. Each presentation was followed by constructive discussions where the Scientific Advisory Board was very active and gave valuable input to the work carried out. All partners including the Board of the Centre were pleased with the progress and obtained results after three years, and emphasized in particular the impressive number of publications in peer reviewed journals.

Seminar in Neckarsulm.

Research programmes and demonstrators

The research in the Centre is based on annual work plans. Thus each research programme and the demonstrator activity is composed of several research projects. The following gives an introduction to each research programme and is followed by highlights from the activities carried out.

Fracture and Crack Propagation (F&CP)

Programme head: O.S. Hopperstad

Introduction

In numerical simulations of quasi-static and dynamic ductile fracture, e.g. in analysis of forming processes, crashworthiness and structural impact, many complex and interacting phenomena generally occur: large deformations, contact, elastic-plasticity, viscous and thermal effects, damage, localization, fracture, length-scale effects and crack propagation. Solving such problems requires advanced numerical techniques.

Today the finite element method is used in most cases, and ductile fracture and crack propagation are typically solved using uncoupled or coupled damage mechanics and element erosion at a critical value of damage. This approach is deemed to depend on mesh size and mesh orientation, and various regularization techniques (e.g. the non-local approach, gradient theories and viscous regularization) have been proposed to enhance mesh convergence. Two examples of alternative strategies are node splitting coupled with adaptive meshing and extended finite element methods (XFEM). There is a need to evaluate established methods against other possible approaches for modelling of ductile fracture and crack propagation, and to make these novel procedures available for industrial use.

In the F&CP programme, mathematical models and numerical algorithms for damage, fracture and crack propagation in ductile materials are developed and validated against laboratory tests. The materials considered are rolled, extruded and cast aluminium alloys, high-strength steels and polymers. In 2009, there have been projects running within the following research areas:

- Numerical aspects of fracture and crack propagation
- Fracture in cast materials – mechanisms and modelling
- Fracture in age-hardening aluminium alloys – mechanisms and modelling
- Plastic instability and localization in metals and alloys
- Optical measuring techniques (PhD project Egil Fagerholt)
- Extended finite element method (XFEM) (PhD project Gaute Gruben)
- Fundamentals of fracture (PhD project Marion Fourmeau)
- Material models for the simulation of aluminium die-castings (PhD project Octavian Knoll)

Selected research activities are briefly described below.

Fracture in cast materials – mechanisms and modelling/optical measuring techniques

An experimental and numerical investigation of the fracture behaviour of the cast aluminium alloy AlSi9MgMn has been completed in 2009. In the experiments, a modified Arcan test set-up was used to study mixed-mode fracture. During testing, the tension load and the displacement of the actuator of the test machine were recorded, simultaneously as a high-resolution digital camera was used to record a speckle-patterned surface of the specimen. The recorded images were post-processed using an in-house digital image correlation (DIC) software to obtain information of the displacement and strain fields in the specimen during the test. In addition, some newly implemented features in the DIC software allowed us to detect and follow the crack propagation in the material. The numerical calculations were carried out with a user-defined material model implemented in an explicit finite element code. In the model, the material behaviour is described by the classical J2 flow theory, while fracture was modelled by

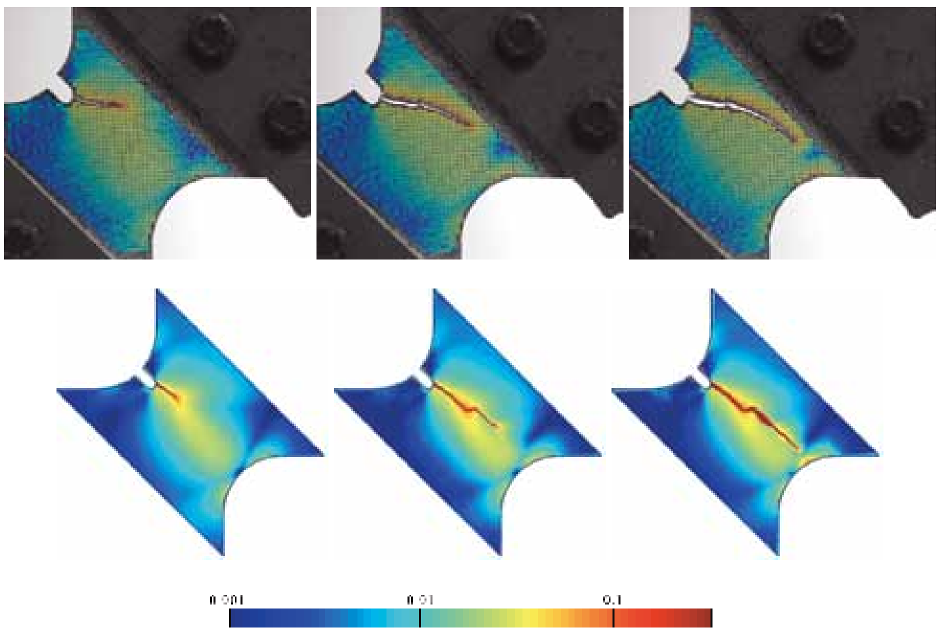


Figure 1 – Equivalent strain fields from experiments (top row) and finite element analysis using stochastic fracture parameters (bottom row) for mixed-mode loading, plotted as logarithmic scaled colour maps. The experimental results are plotted on the current configuration, while the finite element results are shown on the reference (or un-deformed) configuration.

the Cockcroft-Latham criterion, assuming the fracture parameter to follow a modified weakest-link Weibull distribution. With the proposed probabilistic fracture modelling approach, the fracture parameters can be introduced as stochastic parameters in the finite element simulations. Crack propagation was modelled by element erosion, and non-local regularization was used to reduce mesh-size sensitivity. To reveal the effect of mesh density and meshing technique on the force-displacement curves and the crack propagation, several different meshes were used in the numerical simulations of the Arcan tests. The numerical results were finally compared to the measured data, and good agreement was generally obtained between the measured and predicted response. As an example, the equivalent strain fields from experiments and finite element analysis using stochastic fracture parameters are shown in Figure 1 for mixed-mode loading. Note that the experimental results are plotted on the current configuration, while the finite element results are shown on the reference (or un-deformed) configuration.

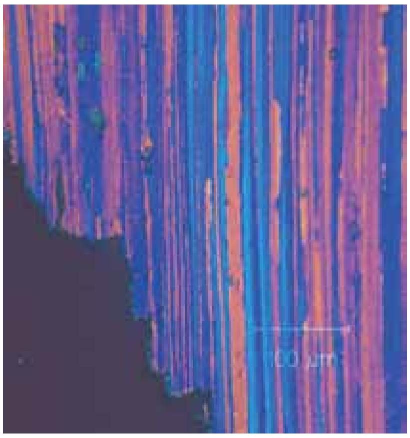
Fracture in age-hardening aluminium alloys – mechanisms and modelling

Age-hardening aluminium alloys of the 6xxx and 7xxx series have complex microstructure, and a diversity of mechanisms for fracture can occur in these alloys. At peak hardness condition, the microstructure consists of grains with a high density of fine hardening precipitates formed homogeneously in the material during artificial aging and a lower density of larger intermetallic constituent particles formed during solidification. Owing to the large deformation during rolling/extrusion, the constituent particles tend to be elongated and aligned along the rolling/extrusion direction. In the non-recrystallized alloys, there is also a high density of dispersoids, which are introduced to avoid recrystallization during thermo-mechanical processing. The grains are either recrystallized with equi-axial or elongated shape or they are non-recrystallized and strongly elongated containing small sub-grains, i.e. a fibrous grain structure. Along the grain (and sub-grain) boundary, a precipitate-free zone (PFZ) is typically formed during aging, which has markedly lower strength than the interior of the grain. Accordingly, the PFZs act as soft zones in which plastic strains tend to localize during deformation of the alloys. Depending on the cooling rate during quenching from solution temperature and the artificial aging process, grain boundary precipitation occurs. The grain boundary precipitates are typically coarser than the fine hardening precipitates in the grain interior, and are considered to lower the ductility of the PFZ. The microstructure of these alloys results in local variation in properties causing localization of strain to the soft areas. On a larger scale both the grain structure and the crystallographic texture can cause variation in the mechanical properties. On a micro scale, intermetallic constituent particles, dispersoids, precipitates and PFZs will contribute to an inhomogeneous strain field and preferential fracture initiation and crack growth.

In 2009, the fracture mechanisms of the fibrous aluminium alloy AA7075 in T651 temper were studied by material tests at various stress states and loading directions, plate impact tests and metallurgical investigations. The ductility (or strain to fracture) was found to depend on both the stress state and the loading direction. The fracture mode was cup-cone or shear depending on the stress state. Macroscopic shear bands were seen in compression, and in tension a combination of trans-crystalline and inter-crystalline fracture was observed. This is illustrated in Figure 2, which presents micrographs of the deformed microstructures and failure modes in uniaxial tension in the rolling direction and in through-thickness compression. In the plate impact tests, delamination and fragmentation were seen at the macroscopic level, while at the microscopic level, the fracture mechanisms resembled those found in the material tests. Based on the test data, a constitutive relation and a fracture criterion were determined for the alloy, and finite element simulations of the plate impact tests were carried out. The main fracture modes were captured in the simulations.

Plastic instability and localization in metals and alloys

It is well-known that for rate-independent solids in the presence of softening, e.g. due to damage evolution or adiabatic heating, the numerical results may be highly sensitive to the spatial discretization. This mesh dependence is often observed in the analysis of localization phenomena and is generally attributed to the lack of a length scale in the continuous description of the constitutive behaviour. Necessary and sufficient conditions for this ill-posedness to occur are known in the case of a linear boundary-value problem. These conditions are respectively the loss of ellipticity of the governing equations, the loss of the boundary complementing condition and the loss of the interfacial boundary condition when the solid is heterogeneous. In the literature, it has been suggested that rate dependence may help avoiding this



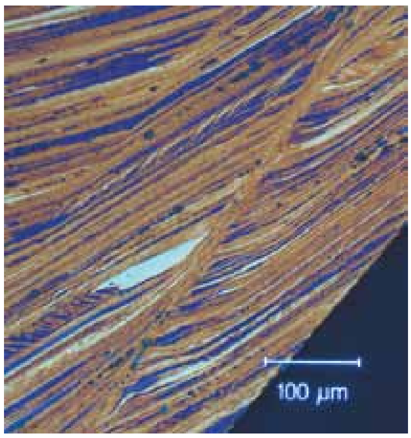


Figure 2 – Micrographs showing the deformed microstructures and failure modes of the fibrous alloy AA7075 in uniaxial tension in the rolling direction (left) and in through-thickness compression (right).

ill-posedness. However, this is only true with some restrictions, and it has recently been shown that a critical time step exists beyond which ill-posedness occurs also for rate-dependent materials. The associated discretized problem is well-posed when the time step is smaller than this limit and one should expect objective computations in this case.

This research activity studied the uniqueness and the loss of ellipticity of the time-discretized boundary-value problem for softening elastic-viscoplastic solid materials. The obtained results show that whenever the time step is chosen sufficiently small non-uniqueness and loss of ellipticity are ruled out, which is consistent with recent mathematical results in the literature. The conditions for uniqueness and loss of ellipticity were established, using an implicit return-mapping algorithm for temporal integration of the rate-dependent constitutive equations. It was established that a critical time step exists beyond which the problem may become ill-posed, leading to well-established pathological mesh sensitivity of the spatial discretization. It is therefore not guaranteed that use of rate-dependent constitutive relations regularize rate-independent boundary-value problems. It is further emphasized that the finite-step problem arising from an explicit time-integration scheme, e.g. the forward-Euler algorithm, is always well-posed, so that non-uniqueness and loss of ellipticity never occur. In this last case, however, numerical instability is expected if the time step is not small enough. We have also shown that possible non-uniqueness and loss of ellipticity are associated with the instability of the continuous, rate-dependent initial boundary-value problem.

A numerical example with a fictitious rate-dependent material with softening (cf. Figure 3, left) showed that loss of ellipticity may occur for relatively small time steps that should be expected in simulations of various problems. It was further observed that the critical time step depends markedly on the stress state, being smallest for shear loading. In the example problem, the critical time step was more than a magnitude larger for axisymmetric than for shear stress states. In Figure 3 (right), the loss of ellipticity under shear loading, signified by negative values of the parameter $\left(H_{n+1}-H_{n+1}^{cr}\right)/H_{n+1}^{cr}$, is illustrated. Here H_{n+1} is a plastic modulus depending on the material properties and the time discretization, while H_{n+1}^{cr} is the critical value of H_{n+1}.

The practical use of the obtained results is to properly select the time step in numerical simulations of problems with softening elastic-viscoplastic materials. One possibility is to choose a time step satisfying the uniqueness criterion. As this would give a lower bound on the optimal time step to be used, an upper bound is provided by the critical time step at loss of ellipticity. A time step chosen between these two bounds will ensure the well-posedness of the discretized rate-dependent boundary-value problem. In this last case, uniqueness is not necessarily guaranteed.

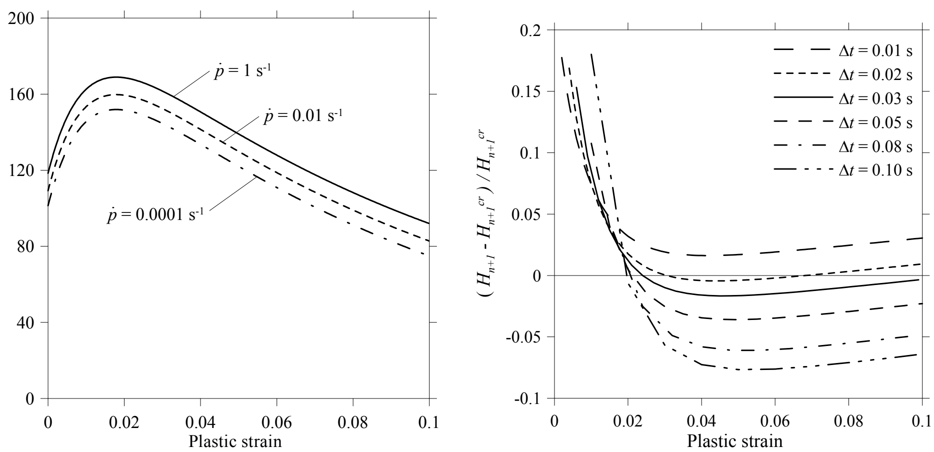


Figure 3 – Stress-strain curves at different strain rate for elastic-viscoplastic material with softening (left) and loss of ellipticity in shear loading signified by negative values of the parameter $\left(H_{n+1}-H_{n+1}^{cr}\right)/H_{n+1}^{cr}$ *(right).*

Optimal Energy Absorption and Protection (OptiPro)

Programme head: T. Børvik

Introduction

From a design perspective explosion, impact, collisions and weapon actions may be classified as accidental loads. These events are becoming increasingly important for a number of civil, military and industrial engineering applications and for the safety of the citizen in general. Since it is both difficult and expensive to validate and optimize protective structures against accidental loads experimentally, product development is increasingly carried out in virtual environments by use of the finite element method (FEM) to have safe and cost-effective design. These new designs need to be validated through high-precision experimental tests involving advanced instrumentation.

The main objective with the OptiPro research programme is to be able to design safer, more cost effective and lightweight protective structures for a variety of engineering applications using advanced computational tools. In 2009, the main focus has been on the following research activities.

1. Strengthening techniques
2. Blast loading using FEM
3. Lightweigh protective structures
4. Impact loading of high-strength steel components
5. Impact against pipelines

Note that there has been a close collaboration between the OptiPro and the F&CP research programmes in 2009.

Blast loading using FEM

Until recently, continuum-based Eulerian approaches were regarded as the most accurate technology for e.g. finite element airbag deployment and blast load simulations. However, a continuum-based approach to the modelling of airbag or detonation gases and their interaction with structural components is subjected to several difficulties. One major problem is that there are geometrical complexities that are hard to handle, both in the gas/structure contact and in the treatment of gas flowing through e.g. narrow gaps. As an attempt to circumvent those difficulties, a corpuscular (or particle-based) method for gas dynamics has been developed. The corpuscular approach is based on Maxwell's kinematic molecular theory and it works with discrete, rigid, spherical particles that transfer forces between each other through contact and elastic collisions. The approach is implemented in the non-linear, explicit finite element code LS-DYNA and is currently further developed in the IMPETUS Afea solver. The method is Lagrangian, which simplifies the gas/structure contact treatment. Also for close-range blast-load applications, such as the description of a mine explosion underneath a vehicle, complex geometries may need to be considered. This type of simulation is known to be extremely CPU-demanding when using a fully coupled Eulerian approach. It is therefore the objective of the current research to investigate whether the recently implemented corpuscular method can be utilized in its basic form to also describe close-range blast loading. It is clear that certain limitations apply to the method when used in its original form to describe the detonation products, but these problems are hoped to be overcome in 2010. The approach is currently based on an ideal gas assumption that deviates from the equations-of-state usually used to describe blast loading (such as the JWL-EOS). Secondly, the method is dispersive. This means that elastic waves are quickly smeared out. The dispersion is caused by a particle mean-free-path that is several orders of magnitude larger than the molecular mean-free-path in a real gas. The approach is thus likely to be best suited to describing close-range blast-loading events.

So far, the method has been described and validated against a simple blast-load test from the literature. In the test, a clamped circular RHA steel plate with a diameter of 1 m and a thickness of 20 mm was exposed to the blast loading from a 15 kg TNT charge with stand-off distance of 1 m, and the peak deflection of the plate during the blast was estimated to be 34 mm. The test was then simulated using an Eulerian model and the JWL-EOS to simulate the high explosive. Then an Eulerian model was run where the high explosive was modelled as an ideal gas, before the corpuscular approach was applied. Figure 4 shows the particles in the corpuscular simulation after initiation and 0.1 ms after detonation, while Figure 5 and Figure 6 show a comparison between the impulse transfer and the centre deflection of the plate from the Eulerian and corpuscular simulations, respectively. The agreement between the two approaches is as seen satisfactory. It has been found that the corpuscular method has the potential to become a very useful tool for simulating close-range blast effects on structures. The method is numerically robust, much less CPU-demanding than similar coupled Langrangian-Eulerian methods and easy to use. Further, the results from the corpuscular method seem to be in good agreement with corresponding Eulerian simulation results and available experimental data.

Lightweight protective structures

The majority of ballistic studies presented in the literature are concerned with the worst-casescenario, i.e. the normal impact condition where the angle between the velocity vector of the projectile and the normal vector of the target is zero. However, in most real cases the projectile will impact the target with some degree of obliquity. In this study the normal and oblique impacts on 20 mm thick AA6082-T4 aluminium plates are investigated both experimentally and numerically. Two different types of small-arms bullets were used in the ballistic tests, namely the 7.62×63 mm NATO Ball (with a soft lead core) and the 7.62×63 mm APM2 (with a hard steel core), fired from a long smooth-bore Mauser rifle. The targets were impacted at 0º, 15º, 30º, 45º and 60º obliquity, and the impact velocity was about 830 m/s in all tests. Cross sections of the targets are shown in Figure 7.

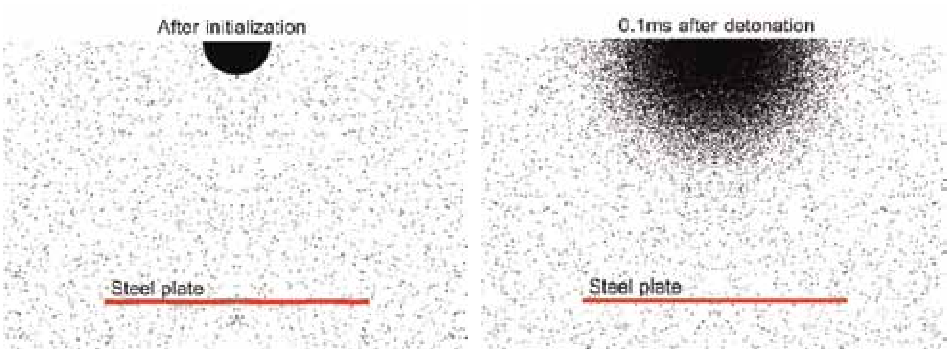


Figure 4 – Corpuscular simulation with 104 particles after initialization and 0.1 ms after detonation.

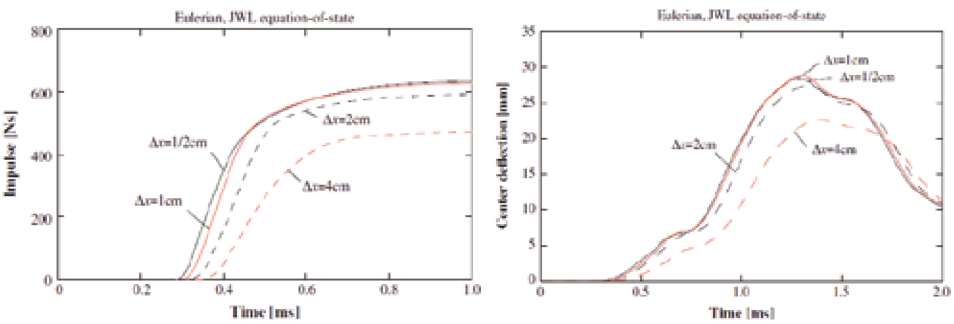


Figure 5 – Impulse transfer and centre deflection of the steel plate when the high explosive is modelled with the JWL equation-of-state (is the element size).

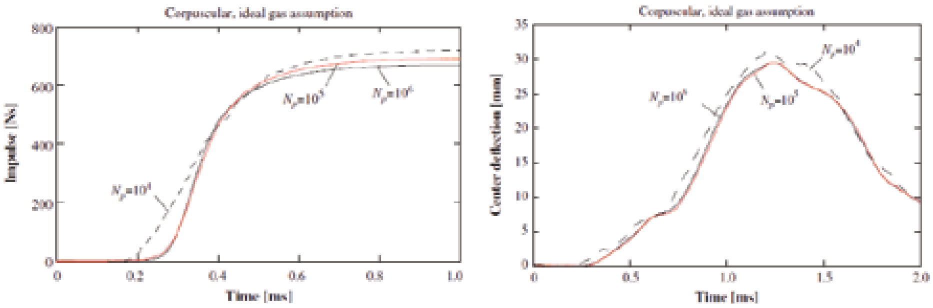


Figure 6 – Impulse transfer and centre deflection of the steel plate when the high explosive is modelled as an ideal gas (Np is the number of particles).

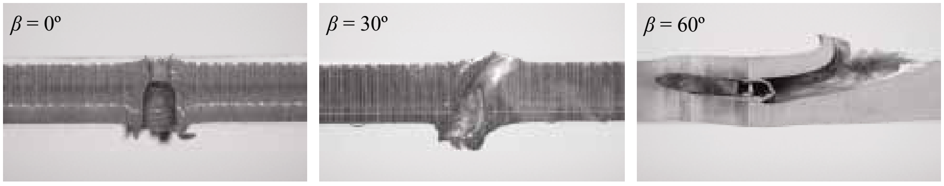


Figure 7 – Sliced target plates after impact by APM2 bullets at increasing oblique angle β.

During testing, the initial and residual bullet velocities were accurately measured by various laser-based optical devices, and two synchronized Photron Fastcam-Ultima APX high-speed video cameras were used to photograph the penetration process. The experimental results for hard core bullets showed that the velocity drop during perforation is almost unaffected by oblique angle to about 30°. For soft core bullets a more continuous drop in velocity with oblique angle was observed. At the highest oblique angles the velocity drop was severe for both bullet types. Of special interest is the critical oblique angle, where the penetration process changes from bullet perforation to ricochet. For this target the critical oblique angle is about 60°. At higher oblique angles, none of the bullets were able to perforate the target plate. A material test programme was also conducted for the AA6082-T4 aluminium plate to calibrate a modified Johnson-Cook constitutive relation and the Cockcroft-Latham fracture criterion, while material data for the bullets mainly were taken from the literature. Then, 3D non-linear FE simulations with detailed models of the bullets were run and the different findings were compared against each other. Good agreement between the FE simulations and the experimental results for the APM2 bullets was generally obtained, while it was more difficult to get reliable FE results for the soft core Ball bullet, Figure 8.

Impact loading of high-strength steel components

The effect of loading history in multi-stage forming process and subsequent crash response is of great concern to the automotive industry as advanced high-strength steels are replacing conventional steels in many applications. A vehicle body structure consists of hundreds of formed components. The process of forming a component changes the properties of the material being used. Hydroforming, roll forming, stamping and stretch forming are some typical operations used for making closure or tube structures. Eventually, these forming processes lead to path changes in the material, meaning that the plastic strains remaining in the part after forming are different in the various directions. This is generally ignored in the design of automotive structures even though the changes in material strength and thickness may be substantial.

Previous studies found out that forming processes have a significant influence on the subsequent behaviour in dual-phase steels. As a consequence, a material model for dual-phase steel taking into account the process effects was proposed. The main objective of this work is to validate the material model, proposed from previous studies, for the real components. In this respect, a door-beam made of dual-phase

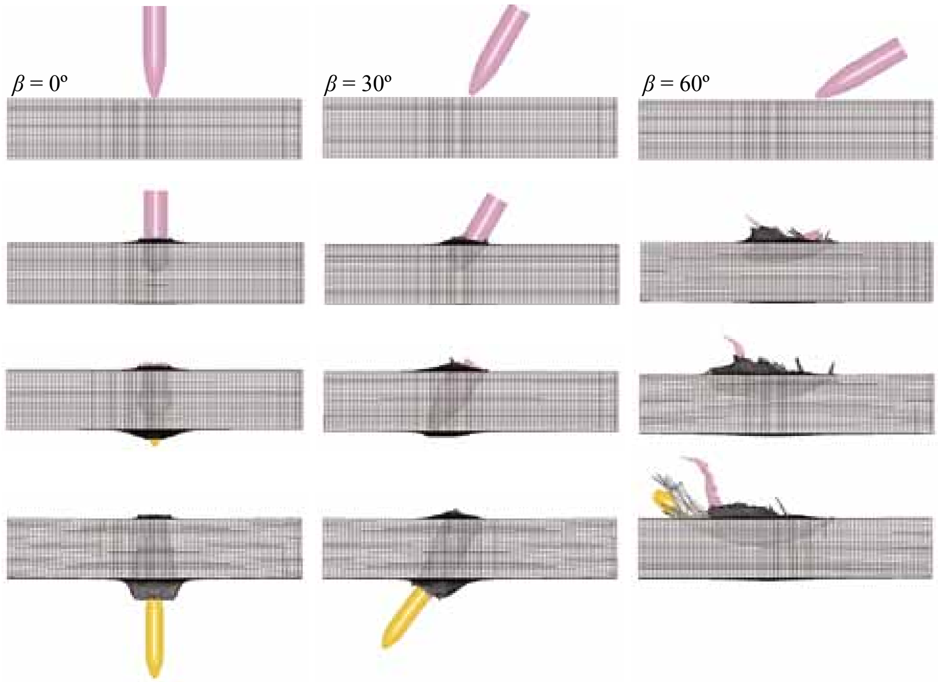


Figure 8 – Plots from 3D simulations using the IMPETUS Afea solver showing the APM2 bullet during impact at increasing oblique angle β.

steel was investigated under stretch-bending. The secondary objective of this work is to validate existing fracture models for dual-phase steel components.

An experimental programme of formed components subjected to stretch-bending has been performed. The initial geometry of the door-beam did not give any fracture and was hence not satisfactory in order to evaluate the fracture part of the material model. The geometry was modified by attaching a bottom plate to the profile. Three successful experiments with the modified geometry have been performed with a stretch force of 5 kN. The next step is to model the forming process in the same FEM program as the stretch-bending simulations in order to adequately map history variables such as the kinematic hardening and fracture parameter. Illustration of test and analyses is shown in Figure 9.

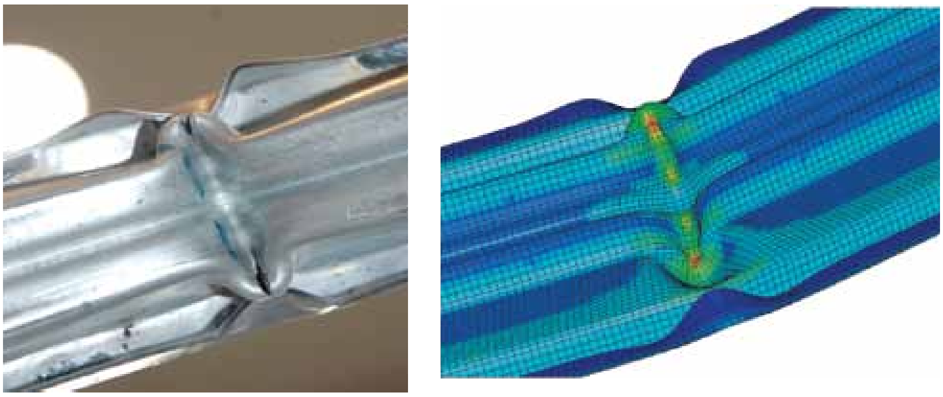


Figure 9 – To the left a picture of one of the experiments is shown at the final stage; to the right the accumulated effective plastic strains are shown for a simulation.

Impact against pipelines

Det Norske Veritas (DNV) has worked out guidelines on how to design subsea pipelines subjected to interference by trawl gear in fish rich areas. One topic of special interest for the offshore industry is pipelines first subjected to impact loading before being dragged along the seabed. Such loading scenarios may introduce both large global deformations and local strains in the pipeline. After impact, the pipe is straightened due to the presence of axial forces. The material in the highly deformed zone will experience a complex stress and strain history, which subsequently can cause fracture. Other accidental loads related to marine activities, such as anchor impacts, may also have to be taken into consideration in the design of sub-sea pipelines. To study these topics, full scale testing is not straightforward and a simplified approach is chosen as a first step in the present activity. Based on the observed local curvature in impacted pipelines, three-point bending tests of beams cut from a typical pipeline have been carried out and subsequently stretched to a straight position, see Figure 10a. One objective of these tests was to investigate if cracking in the pipe could occur after such a loading sequence. Material tests with specimens taken in different

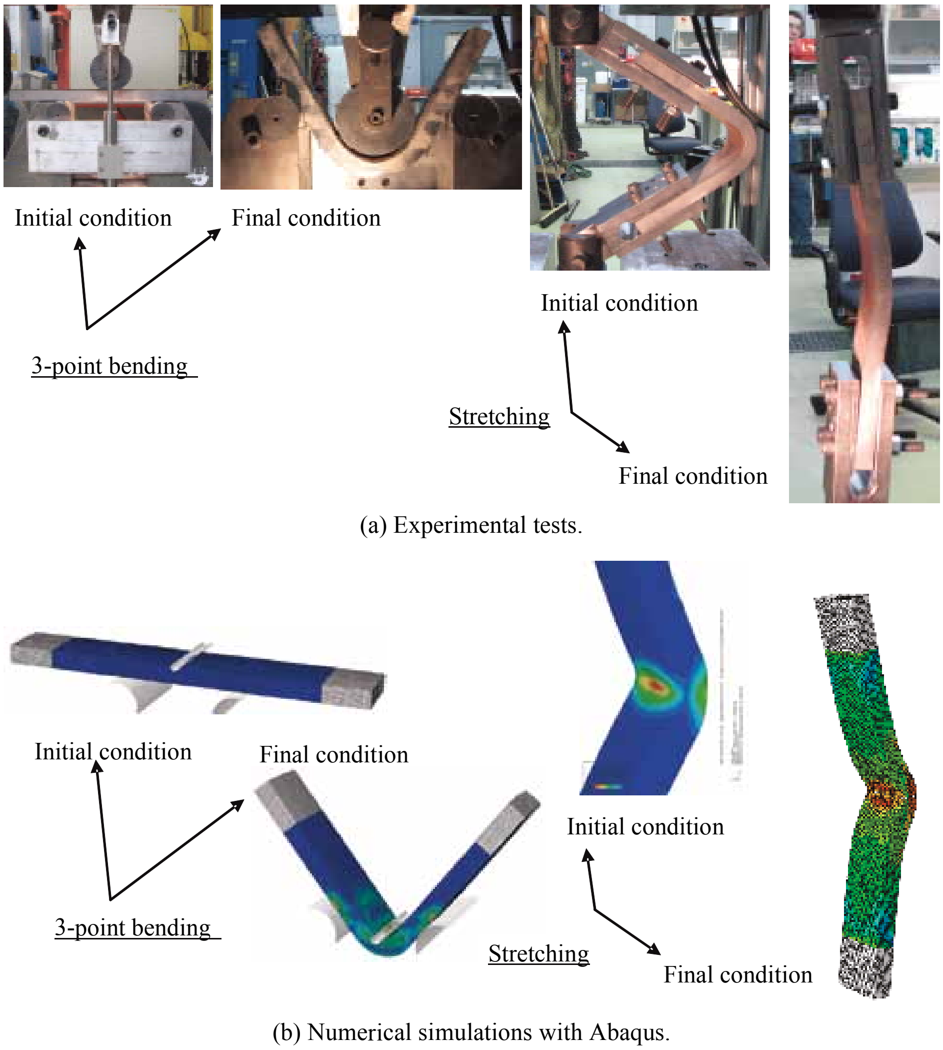


Figure 10 – Experimental tests and numerical simulations on a section of a pipeline material.

directions and at different locations in the actual pipe were carried out to calibrate an appropriate constitutive relation (taking anisotropy and kinematic hardening into account) and a simplified fracture criterion. Finally, numerical simulations of the complete loading process were carried out, and the predicted response was validated against the experimental data, see Figure 10b. The activity will continue in 2010, but then by doing impact and stretching tests and numerical simulations on real pipes.

Polymers (Poly)

Programme head: A.H. Clausen

Introduction

Polymers are promising for use in several applications. In particular, such materials may have excellent energy absorption characteristics. The experience in using polymers in impact protection systems, however, is limited, and there are several challenges which call for research.
One of the most obvious is the lack of robust material models in commercial finite element codes. Some of the features commonly observed for polymers are large temperature and strain-rate effects, pressure sensitivity, deformation-induced anisotropy and viscosity. In general, the behaviour of polymers is fundamentally different from the typical response of metals.

The main objective of this programme is to develop validated material models for polymers subjected to impact. An important prerequisite and sub-goal is to establish a set of test methods for material characterization, and generate a database with results from different component tests. The programme is for the time being limited to thermoplastics, and constitutive modelling has been in focus so far, i.e. failure was not considered in 2009. This will, however, be the topic for a PhD project (Anne Serine Ognedal) in 2010 and 2011.

Plates made of PEHD and PVC are applied in the experimental study. These plates were purchased from a wholesaler, and the two materials, one being semi-crystalline and one amorphous, are generic. It is deliberately chosen to acquire plates of PEHD and PVC because they facilitate easy machining of material test coupons as well as specimens for the validation tests. In addition, one of our PhD candidates (Virgile Delhaye) works with three PP materials delivered by Renault as a part of their contribution to the Centre. Audi has also engaged a PhD candidate (Andreas Koukal) who is affiliated to the Centre.

The Polymers programme can, broadly speaking, be regarded as three activities running in parallel:

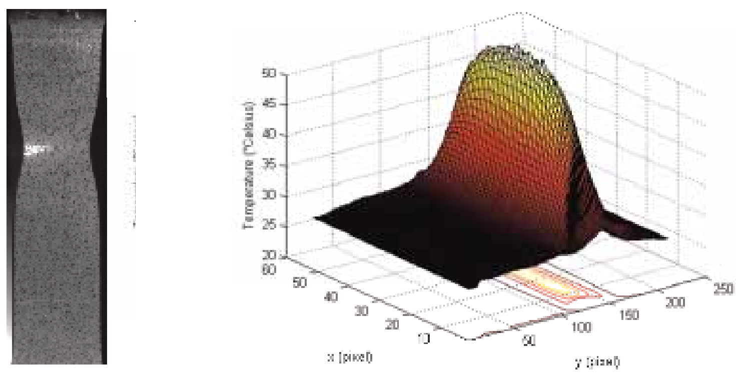
- Material tests
- Constitutive model
- Component tests

Material tests

Thermoplastics have a fundamentally different behaviour from that observed for other materials, e.g. metals, and this calls for some special precautions during material testing. Firstly, a conventional experimental set-up involving an extensometer cannot be employed because of the propagating neck and cold-drawing phenomenon. Also, many thermoplastics change their volume during plastic deformation, and it is therefore necessary to measure transverse strains in addition to the longitudinal strains in order to determine the true stress. As outlined in SIMLab's annual report of 2008, these challenges are treated with an optical measurement technique based on digital image correlation (DIC).

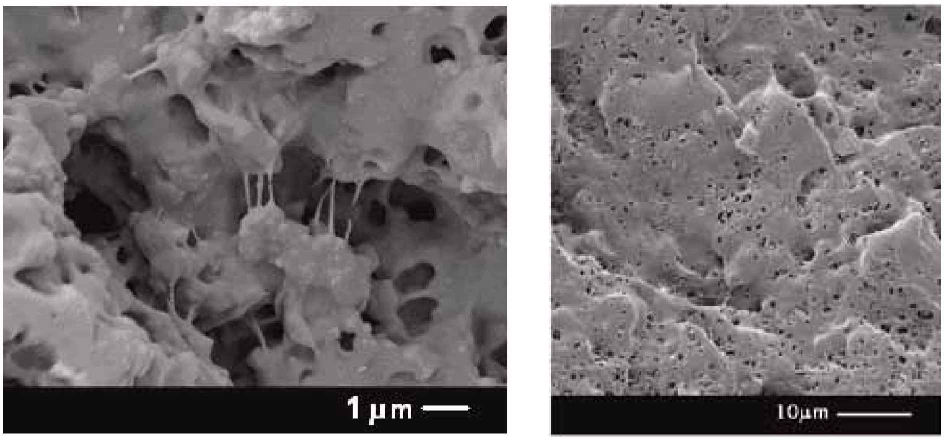
Cooperating with Laboratoire de Mécanique et Technologie at ENS Cachan in France, tension tests instrumented with an infrared camera in addition to DIC have been carried out. Hence, the surface temperature of the sample was measured during the test. Figure 11 shows the temperature field in a PVC specimen tested at a nominal strain rate of 10^{-1} s^{-1}. After the onset of necking, the evolution of plastic deformation is localized in a rather narrow zone, giving an adiabatic heating of more than 20°C. The test series reveals that such a temperature increase occurs when the local strain rate exceeds approx. 10^{-1} – 10^{-2} s^{-1}, slightly depending on material. This change of temperature is likely to affect the mechanical properties of the polymer at hand.

Applying Renault's scanning electron microscope (SEM), the microstructure of a polypropylene material tested at quasi-static and dynamic rates has been evaluated, see Figure 12. Although the magnitude of these two micrographs differs, the voids generated during the deformation process are clearly much larger in the quasi-static than in the dynamic case. The smaller void size after dynamic loading indicates a less ductile fracture. Also, Figure 12b suggests that the material has partly melted. This is in accordance with the observations shown in Figure 11b, i.e. polymers are susceptible to an increase of temperature at high strain rates which eventually may cause melting. The large void fraction depicted in Figure 12 is closely linked to the macroscopic volume increase observed for this and other thermoplastics in tension.



(a (b

Figure 11 – Temperature distribution in tension test specimen (PVC). Nominal strain rate 10^{-1} s^{-1}. (a) Deformed specimen at t = 2.4 s, corresponding to an elongation of 8 mm. (b) Temperature field. The y-axis is in the length direction of the specimen.



(a) (b)

Figure 12 – Micrographs of fracture surface of a polypropylene material after tension tests. (a) Quasi-static strain-rate. (b) Dynamic strain-rate. Note that different scales are applied in (a) and (b).

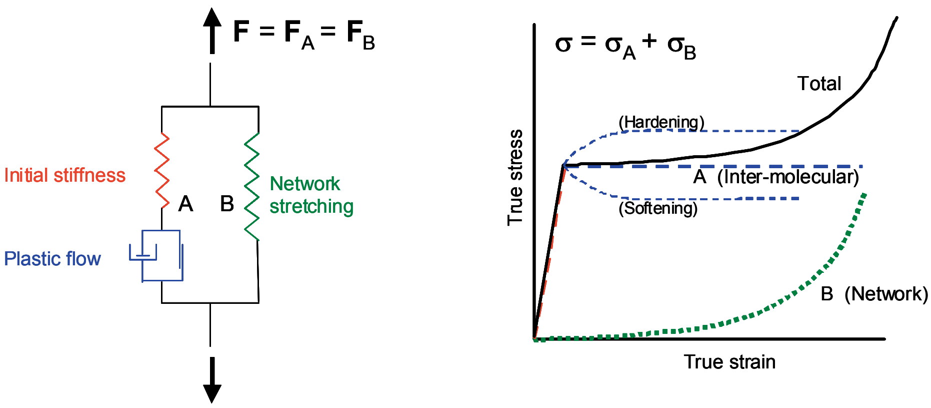


Figure 13 – Outline of the constitutive model for thermoplastics.

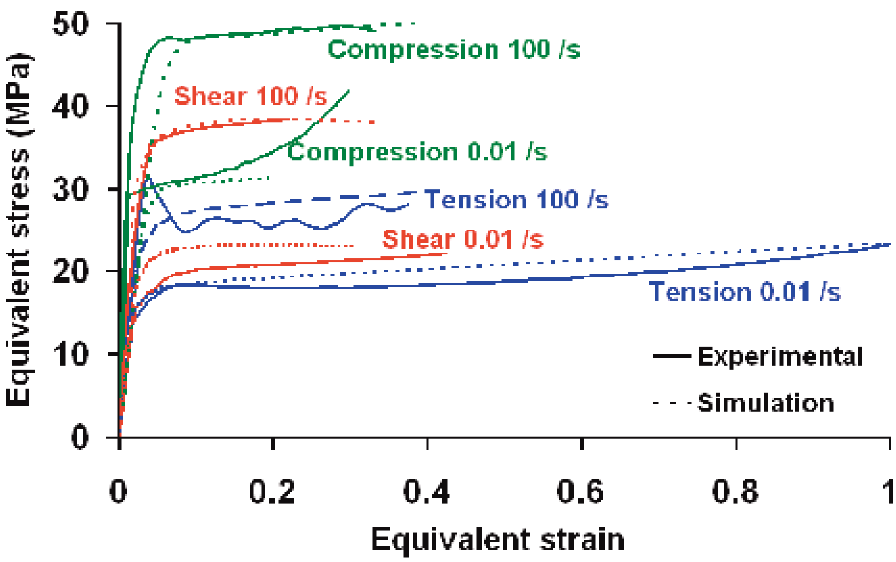


Figure 14 – Equivalent stress-strain curves in tension, compression and shear at different rates for a polypropylene as found from experimental tests and with LS-DYNA applying the constitutive model.

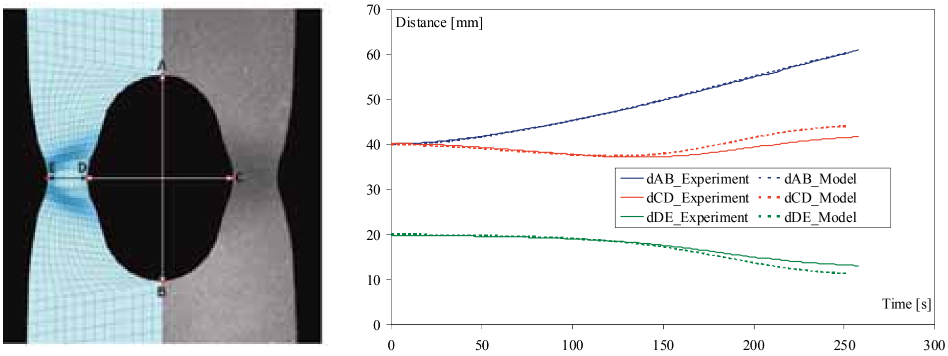
Constitutive model

A constitutive model for thermoplastics is under development. The model captures important features observed in polymers' behaviour such as strain-rate sensitivity, difference between tension and compression, and presence of volumetric plastic strain. A fundamental assumption, see Figure 13, is that the stress σ is the sum of the stresses in a Part A representing the interaction between the molecules in the polymer, and a Part B due to straightening of the molecule chains. The model takes also large-deformation kinematics into account. It was slightly modified in 2009 in order to have a sufficiently stringent formulation, and a possibility for hardening or softening was included. The model contains 12 coefficients which can be identified from uniaxial tension and compression tests. Figure 14 shows that the model is able to represent the response of a materal test specimen at different loading modes and strain rates.

Component tests

Precision tests on components subjected to relevant loading and deformation modes are an important prerequisite for evaluation of a constitutive model. While Figure 14 compares experimental and numerical response for material test samples, a more independent check of the capabilities of the model is obtained by using one set of tests, typically tension and compression tests, for calibration of the coefficients in the model, and separate component tests for the validation purpose. Of course, these components have to be made of the same material as was investigated in the material tests. These experimental benchmark tests should be well-defined with respect to geometry, boundary conditions, application of load, etc.

This evaluation of the model will continue as one of the most important activities within the Polymers programme in 2010. As an example of the benchmarking carried out so far, Figure 15 shows how the deformation of a 80mm wide polyetylene sheet with a hole Ø40mm is predicted by the constitutive model. The FEM mesh and a photo of the physical test at a certain deformation stage is presented in Figure 15(a).



(a) (b)

Figure 15 – Deformation of a polyetylene sheet with a hole. (a) Overview of FEM model and experimental response. (b) Evolution of diameter AB (dAB), diameter CD (dCD) and net half-width DE (dDE).

More details are given in Figure 15(b), addressing the diameter change of the hole and the net width adjacent to the hole. Clearly, the numerical model is able to provide a reasonably accurate prediction of the physical behaviour.

Multi-scale Modelling of Metallic Materials (M^4)

Programme head: O-G. Lademo

Introduction

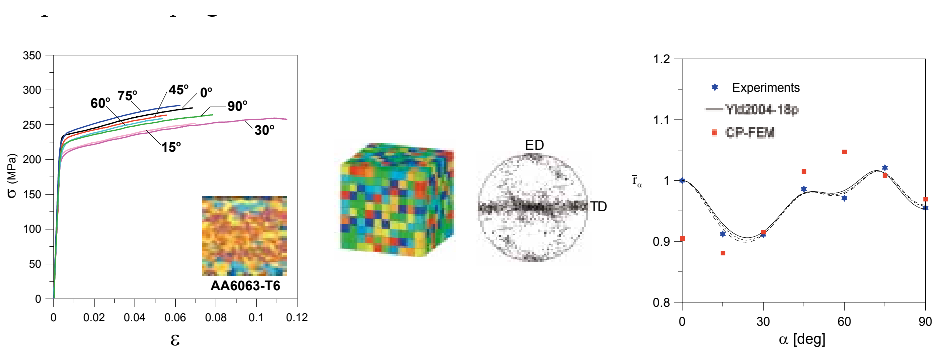
Automotive manufacturers need suppliers who can develop cost efficient, optimized solutions and products with high customer value in a sustainable manner. In the long run the winning suppliers will be the ones who can realize an integrated perspective of their alloy, process and product development. The integrated perspective requires, quite generally, quantitative models, where as many quantitative links as possible must be established, so that needs with respect to a product's cost and performance can be addressed along the value chain. Further, quantitative links and tools are required at all levels to reduce development time and costs (e.g. reduced engineering costs, reduced tooling/trimming, reduced number of prototypes and optimized performance/ weight ratio).

During the later years rather accurate phenomenological constitutive models of metals have been developed and made available in commercial FE codes. These models represent the macroscopically observed behaviour (e.g. work hardening, anisotropy, process effects) on the basis of continuum mechanics. However, they do not provide any information about the physical mechanisms responsible for the observed material response. Hence, the models do not contribute in enhancing the understanding of micro-mechanisms of plastic deformation and offer limited action upstream in the material processing chain. A complementary approach consists of looking at the metal, or polycrystal, from a physical point of view. In this approach the material response is described on the basis of the elementary mechanisms governing the macroscopically observed phenomena. This approach is required for the design of optimized process chains, for the development of next-generation phenomenological models, and for reducing material characterization costs. The physical models are often computationally expensive and can not replace the phenomenological models. Instead an optimized use of the models at various scales must be found.

In the M^4 research programme, modelling frameworks at continuum and meso-crystal level have been established. Within these frameworks, lower-scale model approaches are used to represent micro- and nano-structural features of the materials. Below, some of the results achieved in 2009 are highlighted, divided between fundamental strategic development and application oriented projects.

Fundamentals of multiscale modelling

Over the last two years, a framework for single- and polycrystal plasticity has been developed and implemented into the finite element code LS-DYNA (i.e. an FE-based crystal plasticity approach, here denoted CP-FEM). In 2009, a mechanism study using CP-FEM has been performed. The study tries to identify the cause of the anisotropic hardening and related anisotropic elongation in uniaxial tensile tests, as observed for AA6063-T6. Understanding the phenomenon is important for the development of improved phenomenological models e.g. for further achievements within the modelling of the materials' (de-)formability. Various investigations have been undertaken. At first, a representative volume element (RVE) of the microstructure in the material was modelled by a cube, in which each element represented one grain, see Figure 16. The grain orientations were mapped from



a) b) c)

Figure 16 – Methodology for studying anisotropic hardening due to texture effects in AA6063-T6; a) experimental tensile tests, b) RVE and texture, c) comparison between experiments and simulations on flow stress ratios.

from Electron Back-Scattering Diffraction (EBSD), while the work hardening parameters were identified from tensile test data using the optimization programme LS-OPT.

Shear tests were then simulated in which CP-FEM was used in the shear zone while a phenomenological elastic-plastic model was used for the sample body, see Figure 17.

This simple methodology detected some anisotropic hardening caused by texture effects. The study revealed flaws in the methodology, attributed to the identification procedure and lack of periodicity in the boundary conditions on the RVE. Tools for generation of periodic microstructures and boundary conditions for RVE have been developed which will enable new capabilities for future application oriented problems, Figure 18. At the end of 2009, post doc Afaf Saai was recruited to work with CP-FEM.

Application oriented activities

An extensive experimental test series addressing formability and fracture under non-proportional loading paths has been performed on as-rolled and pre-deformed aluminium sheets. Through this test series the BUP600 formability test machine has been used, including the adoption of strain-field measurement techniques. The test series addresses the industrially important rolled AA6016 alloy with particular emphasis on the failure phenomenon caused by through-thickness shear instability. Two project candidates have been linked to the activity, who in 2010 will write their master's thesis on numerical analysis of selected experimental tests. Example of results from experimental Marciniak-Kuczynski formability test are shown in Figure 19.

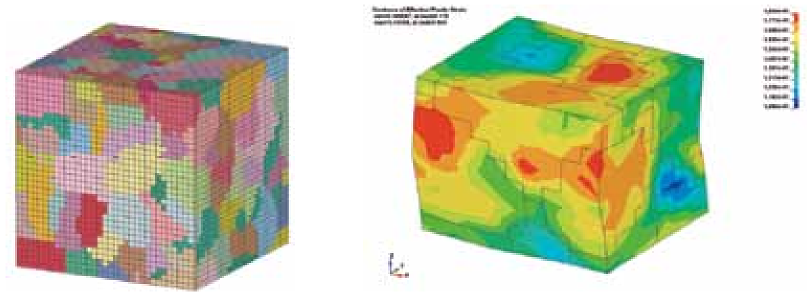


Figure 18 – Periodic RVEs in terms of both microstructure and periodic boundary conditions.

Past experimental series have documented that the strain-rate sensitivity on the strength of rolled aluminium alloys is significant. Two distinct models for strain-rate sensitivity effects have been proposed; one for materials demonstrating positive strain-rate sensitivity and another for materials exhibiting dynamic strain ageing, the associated negative strain-rate sensitivity and the Portevin-Le Châtelier (PLC) effect. An example of positive strain-rate sensitivity response of alloy AA3103 is given in Figure 20, along with associated model representation.

Several activities have been run in connection with the 'through-process' modelling approach for the analysis of the properties of welded structures. The concept relies upon the thermal module of the FE code WELDSIM for welding simulations, advanced microstructure models for the precipitate evolution during welding and heat treatment, and microstructure-based models for strength and work hardening, see Figure 21.

One journal article on the underlying work hardening model has been submitted for possible publication. A second journal article has been finalized, submitted and accepted for publication. This latter article presents a numerical study that, on the basis of the established model concept, evaluates available solutions methods for finite element (FE) simulations of plastic failure in the heat-affected zone (HAZ) of welded aluminium structures. As part of

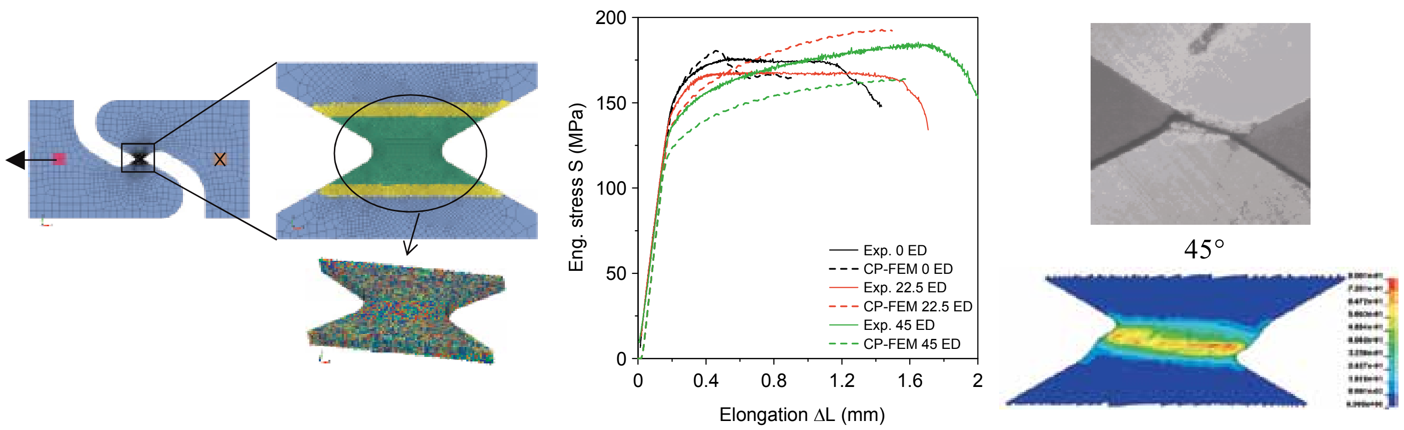
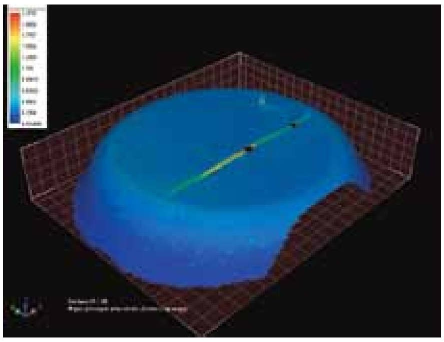


Figure 17 – Modelling of shear test on AA6063-T6; a) finite element model where the green area is described by CP-FEM; (b) stress-elongation curve with comparison between experiments and simulations and c) localization.

a)



b)

Figure 19 – Example of results from experimental Marciniak-Kuczynski formability test (equibiaxial) on pre-strained 6016-T4 sheets a) image taken at failure initiation and b) major strain at failure initiation.

a PhD project an extensive experimental programme on cross-weld tensile tests has been documented. The investigation covers cross-weld tensile tests and hardness measurements of six alloys in two initial conditions with four Post-Weld Heat Treatment (PWHT) processes. Numerical analyses have been undertaken aiming for a quantitative evaluation of the predictive capability of the proposed modelling approach, see Figure 22. Preliminary results indicate that the force level is well captured by the model approach. For the PWHT schemes giving highest strength, premature strain localization is predicted. This calls for a refined work hardening description at large plastic strain, which is currently under development.

A project on the bake hardening effect in advanced high-strength steels has been initiated. So far a literature survey and an experimental programme have been performed and documented. The experimental test series covers the materials DOCOL 600DP, DOCOL 1000DP and DOCOL 1200M, and were performed by SSAB. On basis of the literature survey and experiments, a model has been proposed for the representation of the phenomenon. The activity continues in 2010 with model implementation, numerical studies and directed experimental test series.

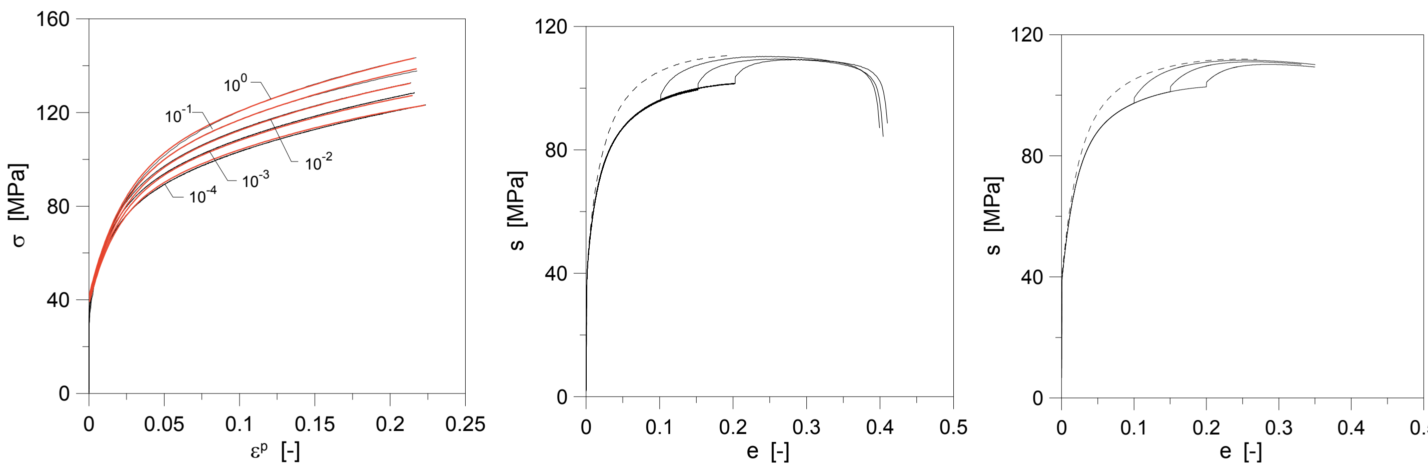
Connectors and Joints (C&J)

Programme heads: R. Porcaro (until November 2009) and A. G. Hanssen (from November 2009)

Introduction

The connection between two or more structural members is denoted a structural joint, and is very important for the strength, ductility and safety of the structure. The strength of each individual connector is well documented in the relevant structural standards, but this information is not sufficient for large-scale simulations as their complete load-deformation characteristics are not given. By use of FEM, detailed 3D models can be established and used for studies of the local joint performance including failure. However, due to the computational expenses, such models cannot be directly used in large-scale simulations and shell-based models have to be used. Such models have to produce robust and reliable results from the onset of loading until failure.

In this programme experimental methodologies and set-up will be developed to characterize the behaviour of connectors subjected to static and dynamic loading conditions. Furthermore, based on the experimental results models for large-scale



a) b) c)

Figure 20 – Positive strain-rate sensitivity of AA3103, a) experimental and model data for steady-state strain-rate tests, b) and c) experimental and predicted results, respectively, for strain-rate jump tests.

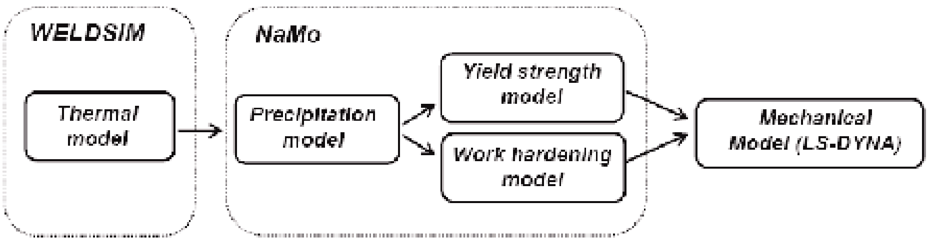


Figure 21 – Through-process modelling concept combining WELDSIM for thermal analysis, NaMo for calculation of the resulting microstructure field, and LS-DYNA for the mechanical analysis.

FE simulations using shell elements will be derived and validated.

During the last three years this programme has mainly focused on the behaviour and modelling of self-piercing riveted structures. A new experimental test set-up was developed for the testing of riveted connections of different materials and a new model for self-piercing riveting (SPR) point connector model was developed and implemented in LS-DYNA. In addition, an activity has started to study self-piercing riveted connections of two aluminium sheets using an aluminium rivet.

Selected research activities are highlighted below.

SPR point-connector model

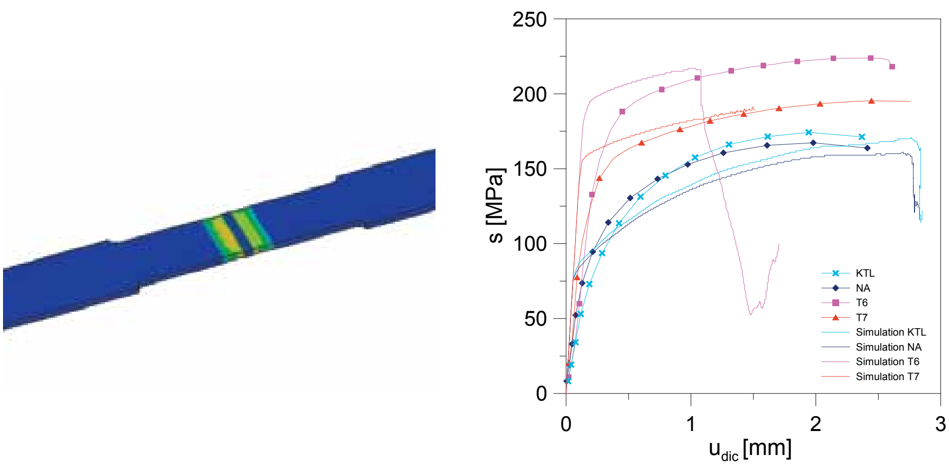
A new SPR point-connector model was developed during the last two years. The model was calibrated against experimental results obtained using self-piercing riveted connections of aluminium-to-aluminium sheets. The model has been show to give good results and is able to accurately replicate the mechanical behaviour of single self-piercing riveted connections under different loading conditions. In 2009, a new experimental set-up was designed in order to validate the SPR model for components including several self-piercing rivets, Figure 23a. In this set-up, several rivets are used to connect a plate to two aluminium extrusions. The plate can be made in aluminium or steel, giving the possibility to test different material combinations. The rivets connecting the plate to the extrusions are subjected to different loading conditions, from a combination of shearing and peeling to a combination of pull-out and shearing. Experimental tests have been performed in quasi-static and dynamic conditions. Different configurations have been used varying the number of rivets, positions of the punch, and plate material. Figure 23a shows some typical results. The model has so far been used to simulate the quasi-static tests. The results are given in Figure 23b. As can be seen the model predicts a premature failure of the rivet connections. Further work will be done to investigate this.

Riveting process using aluminium rivet in combination with local heating

A study was initiated at SIMLab in order to investigate the possibility of replacing the steel rivet with an aluminium one. The use of an aluminium rivet is a challenging task due to its lower stiffness and strength compared to high-strength steel. The rivet needs to have sufficient stiffness and strength to penetrate the top plate, to flare into the bottom one and to create a "good" mechanical interlock. A feasibility study on the possibility to combine the self-piercing riveting process with local heating was initiated in 2009, Figure 24. The local heating was used to soften the sheet materials and increase the possibility to join two aluminium sheets with an aluminium self-piercing rivet. The induction heating equipment available at SIMLab was adapted for this application. A new coil shape was design to heat up the sample before the riveting, Figure 24. Self-piercing riveting tests were performed after heating the plates. The effect of different parameters was investigated, i.e. maximum temperature in the plates and time between the heating process and the riveting process.

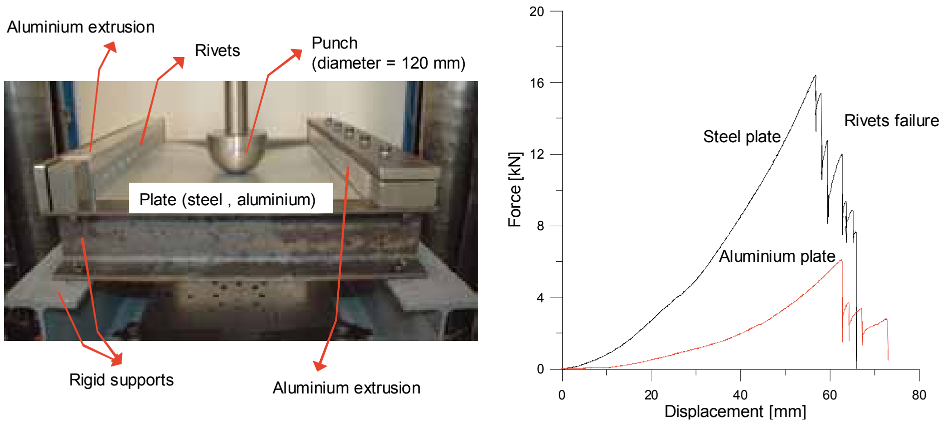
Riveting process using aluminium rivet without local heating

In this study, focus is shifted to apply a high-strength aluminium rivet in order to join aluminium sheets without the corresponding use of local heating as described in the previous activity. In the first phase, two sheets of aluminium alloy AA6060 in three different tempers (W, T4 and T6) were joined by using an aluminium rivet in three different alloys, 6082-T6, 7108-T5 and 7278-T6. Commercial rivet and die geometries were used. The results showed that a successful joint was only obtained for rivet material AA7278-T6 when used for joining plates in AA6060-W condition. In parallel, the behaviour of an aluminium riveted connection subjected to quasi-static loading

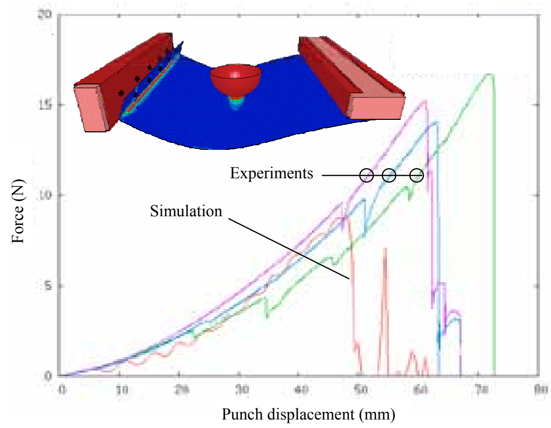


a) b)

Figure 22 – a) Example of predicted strain localization in shell-based model of a cross-weld tensile test b) preliminary comparison between experimental and predicted response in cross-weld tensile tests of AA6060 subject to various PWHT.



a) Testing



b) Validation

Figure 23 – Testing and numerical simulations.

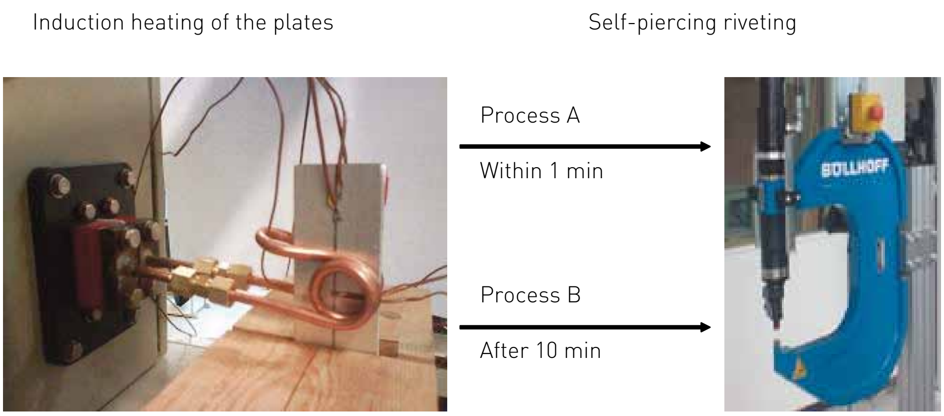


Figure 24 – Self-piercing riveting in combination with local heating.

conditions was studied during 2009. The experimental investigation has shown that the mechanical strength of aluminium riveted joints is comparable with joints using steel rivets, Figure 25. The influence of the pre-straining of the plates due to the riveting process as well as the natural aging of the plates in W temper conditions was also investigated. Extensive experiments have shown that there is an interesting combined effect between these two aspects, see Figure 26. The pre-straining in W temper leads to a lowering of the flow tress of the reloaded materials, i.e. the flow tress of pre-deformed materials in W temper was much lower compared with the stress of the 'virgin' curve at the same equivalent strain, and after the same natural aging. Numerical analyses have shown that it is very crucial to take this lowering effect into account in order to predict the behaviour of the riveted connections with a good accuracy.

However, the W temper is too soft a temper for commercial purposes. Thus, the second part of the project will focus on rivets with higher strength resulting from an E-CAP process and the possibility for these rivets to joint AA6060 alloys in T4 temper.

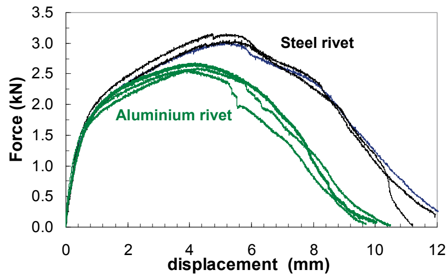


Figure 25 – Mechanical behaviour of riveted connections

Modeling of road restraint systems

This activity focuses on steel road restraint systems which deform during a vehicle impact. The safety barrier is made of w-beam rails and sigma posts. The rails are fastened to the sigma post by a bolt and a hex-nut. During a crash situation these bolted connections may fracture, causing release of the w-beam from the sigma post. This will again have a significant

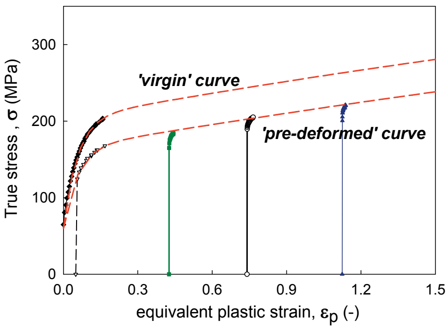
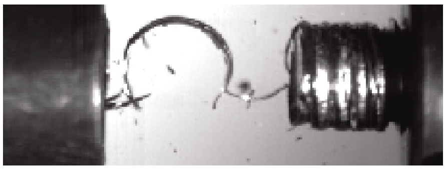


Figure 26 – Stress-strain curves after 3 days of aging obtained from pre-deformed materials in W temper plotted along with the 'virgin' curve.

effect on the performance of the guardrail system. Thus, the aim of this activity is to get improved understanding on how bolted connections behave during a vehicle impact.

In 2009 focus has been on finite element analyses of M5 threaded fasteners exposed for tension load at elevated rates of strain. Different numerical models have been made with the aim to capture the influence of the length of thread engagement. Two different failure modes occurred in the component tests and simulation; bolt fracture in the cross-section area, or fracture due to thread stripping, see Figure 27.

It was observed from tests and simulations that the grip length (the free length) had an influence on the tensile strength of the thread assembly. If the grip length was reduced, the tensile strength of the bolt was increased due to strain rate effects. As a result of the reduced amount of grip length, the bolt necked inside the tapped hole, within the length of thread engagement. This had an influence on the failure mode, and it was possible with the numerical model to change the failure mode from bolt fracture to thread stripping just by reducing the number of exposed threads within the grip at the same test velocity.



a) From high speed camera during test

b) Post experiment

Figure 27 – Thread fastener exposed to thread stripping at high strain rates.

Industrial Demonstrators (Demo)

Programme head: O-G. Lademo

Background

The research areas defined in SIMLab address the fundamental and generic aspects of the behaviour and modelling of an impact loaded structure, i.e. material models and response characteristics of generic components and joints, with emphasis on numerical solution techniques. In real structures a wide range of loading modes, materials and types of connectors have to be considered. Furthermore, each component might have been subjected to a thermo-mechanical process in the form of shaping and aging, the effect of which must be captured in the numerical model. The applicability and feasibility of the various models can only be assessed when tested on full-scale industrial systems, here denoted demonstrators. The main objective of this research area is to establish a link between the basic research and real structures for validation and possible refinements of the developed technology.

In 2009, one project was initially planned for, on the Multi-material welded bumper beam system, see Figure 28. In addition, the programme has supported Audi in their strategy for future industrial utilization of the research-based material models.

Multi-material welded bumper beam system

This project is a continuation of projects run in 2007 and 2008 linked to the through-process modelling concept for welded structures, developed in the research programme Multi-scale Modelling of Metallic Materials. In 2009, the principal focus has been to further refine an industrial modelling guideline that fully exploits the potential of a new modelling concept in an industrial context. The work harvests information from basic studies, in particular on cross-weld tensile test, and combines this information with verification and demonstration on complex structures. Workshops have further been arranged at Hydro Automotive Structures to further support and facilitate the industrial implementation of the methodology.

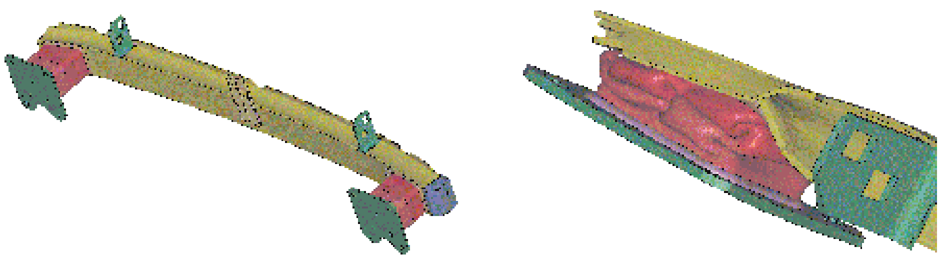
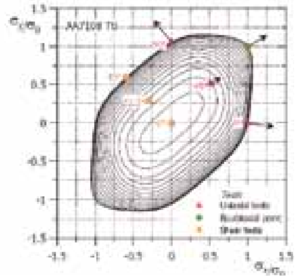
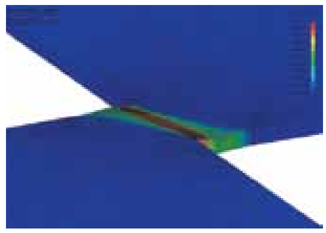
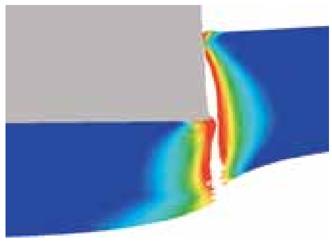
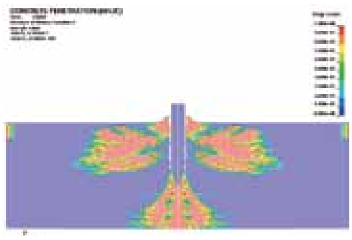
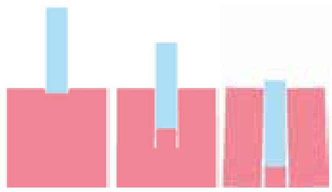


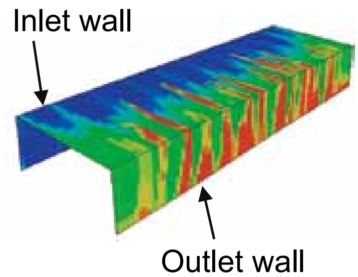
Figure 28 – Full-scale crash analysis of welded bumper beam system exploiting the through-process modelling concept.

SIMLab material model library

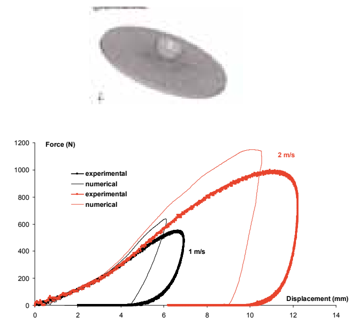
Some principal outcomes of CRI SIMLab are numerical implementations of constitutive models and failure criteria. Some of the models have been initiated in past projects and refined through SIMLab projects, while other models have been initiated within SIMLab.

MATERIAL MODEL	DESCRIPTION	
WTM/STM-2D	Metal plasticity model based on Hosford-class anisotropic yield criteria Yld89 and Yld2000-2D for realistic and direct FE-based prediction of instability and fracture in sheet metals. **Key applications:** Shell based forming, formability/fracture and crashworthiness analysis of metallic materials, components and structures.	
GSTM	Metal plasticity model based on Yld2004-18p anisotropic yield criterion for realistic and direct FE-based prediction of instability and fracture in sheet or thick-walled metals. **Key applications:** Shell- and brick-based forming, formability/fracture and crashworthiness analysis of metallic materials, components and structures.	
MJC	Johnson-Cook metal plasticity model approach with modified strain-rate terms, added strain hardening term and fracture criteria. **Key applications:** Numerical analysis of impact and projectile/fragment penetration analysis.	
MHJC	Modified Holmquist-Johnson-Cook material model for solid geo-materials. **Key applications:** Numerical analysis of impact, and projectile/fragment penetration analysis for e.g. concrete, rocks and ceramic materials.	
MDF	Crushable foam model based on the yield criterion of Desphande-Fleck with stress- and strain-based fracture criteria. **Key applications:** Mechanical analysis of crushable foam materials.	

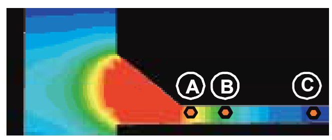
MATERIAL MODEL	DESCRIPTION
TPCM	Model for high-pressure die cast aluminium and magnesium with coupling to the MagmaSoft casting simulation tool, for efficient and realistic incorporation of process effects and probabilistic fracture. **Key applications:** Fracture and crashworthiness analysis of high-pressure die castings.



MATERIAL MODEL	DESCRIPTION
POLY	Polymer model - Refined modelling approach based on the work of Boyce and others, incorporating finite strain elasticity, a pressure dependent yield criterion (Raghava), and a non-associated plastic flow rule. **Key applications:** Mechanical analysis of thermoplastic components.



MATERIAL MODEL	DESCRIPTION
HAZ-2D	HAZ model for welded aluminium structures with option of obtaining material parameters through welding simulations using WELDSIM (mapping or position-dependent properties). **Key applications:** Shell-based fracture and crashworthiness analysis of welded aluminium structures.



Tailored development on the associated solution techniques further covers:

- Non-local plastic thinning: Regularization technique applicable for shell-element analysis using small elements (in particular, less than the shell thickness).
- Non-local plastic instability criterion for detection of incipient unstable thinning i.e. for formability predictions.
- Technologies for proper and efficient crack propagation modelling: Node splitting and fission adaptivity.
- Point connector model for self-piercing rivets.

SIMLab test facilities

The laboratory at SIMLab/Department of Structural Engineering is equipped with a number of special-purpose testing facilities. Some of these facilities are applied to material characterization at elevated rates of strain and at different stress states. Other test rigs are used for impact testing of components and structures for validation of numerical models.

Material testing at elevated rates of strain

Split-Hopkinson tension bar (SHTB)

The split-Hopkinson tension bar, see Figure 29, is a device for material testing at strain rates in the range between 200 and 1500 s^{-1}. It consists of two steel bars with diameter 10 mm. They are denoted input and output bars, having lengths 8 m and 7 m, respectively. The sample is mounted between the two bars. Before the test, the input bar is clamped by a locking mechanism located 2 m from the sample. Thereafter, the external 6 m of this bar is prestressed by means of a jack attached at the bar's end. By releasing the lock, an elastic stress wave is released, propagating towards the sample with a velocity of 5100 m/s. Applying one-dimensional stress wave theory, the response of the specimen, i.e. stress, strain and strain rate, is determined from records of strain gauges glued to each bar. High-speed camera instrumentation is also feasible. Moreover, an induction heater fascilitates tests also at elevated temperatures.

The rig has been used for strain-rate characterization of different steel, aluminium and magnesium alloys. High and low temperature tests have been carried out for steel and aluminium. Two designs of the test samples are possible; axisymmetric with diameter 2-3 mm in the gauge part, or sheet with thickness 1-2 mm and width 3 mm.

FOR MORE INFORMATION:
Chen Y., Clausen A.H., Hopperstad O.S. and Langseth M.: Application of a split-Hopkinson tension bar in a mutual assessment of experimental tests and numerical predictions. Submitted for possible publication.

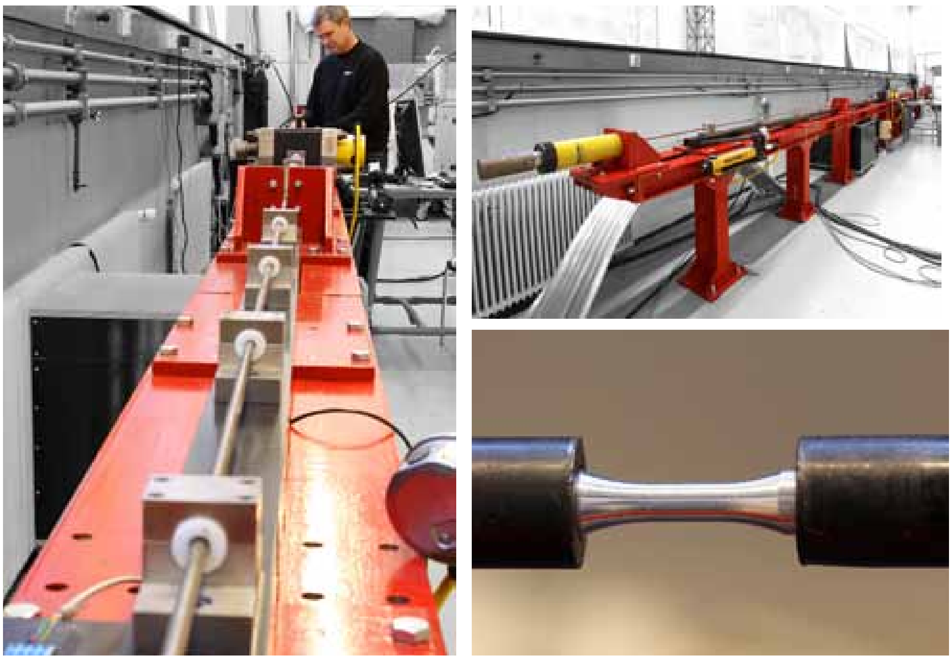


Figure 29 – Split-Hopkinson tension bar.

Photo: Melinda Gaal.

Hydro-pneumatic machine (HPM)

The hydro-pneumatic machine (HPM), shown in Figure 30, is a device for tensile material testing and are operating in the strain-rate range between 1-200s^{-1}. The diameter of the shafts is in the range 8–12 mm. The facility is operated by gas and water and has a lightweight movable piston made of steel or aluminium. The movement of the piston is controlled by the difference in pressure between the two chambers. Prior to testing, both chambers are brought to equal pressure by introducing nitrogen gas in one chamber and water in the other. The pressure difference is established by firing a rapid valve located in the exhaust line to the water chamber causing a rapid evacuation of the water through an orifice, thus allowing the piston to move at a constant velocity and stress the test specimen to fracture. The piston velocity and the hence the rate of loading is controlled by the size of the orifice. The load applied to the specimen is measured by using strain gauges on the bars which behave elastically during testing. The specimen elongation is measured by means of a displacement transducer.

The facility can be operated at low and high temperatures with the same instrumentation as for the SHTB. So far the test rig has been used to characterize steel and aluminium alloys at elevated rates of strain and temperatures.

FOR MORE INFORMATION:
Tarigopula V., Albertini C., Langseth M., Hopperstad O.S., Clausen A.H.: *A hydro-pneumatic machine for intermediate strain-rates: Set-up, tests and numerical simulations.* 9th International Conference on the Mechanical and Physical Behaviour of Materials under Dynamic Loading, Brussels, Belgium 7-11 September. DYMAT2009 (2009) 381-387.

Sheet metal testing machine (BUP 600)

This fully PC-controlled multi-purpose hydraulic sheet metal forming machine, see

Figure 31, is designed for formability testing of sheet metals in accordance with the most common standards and procedures. Its main advantages are an easy and rapid inter-changeability of the test tools, availability of tools for all well-known test standards and procedures, low cylinder-piston frictions delivering accurate measurement acquisitions and excellent reproducibility, and numerous modular possibilities of extensions. These features make this machine an excellent mean for performing advanced research in studying forming processes and for validation of numerical models as well as for educational training of master's and PhD candidates. The machine has a 600 kN load capacity, a maximum clamping force of 50 kN, a maximum test stroke of 120 mm and a maximum test speed of 750 mm/min. The machine at SIMLab has currently tooling for earing tests, Nakajima and Marciniak-Kuczynski formability test set-ups, square cup drawing tests and bulge tests. Although the intention of the machine is to test sheet metals, it can also be applied with samples made of thermoplastics.

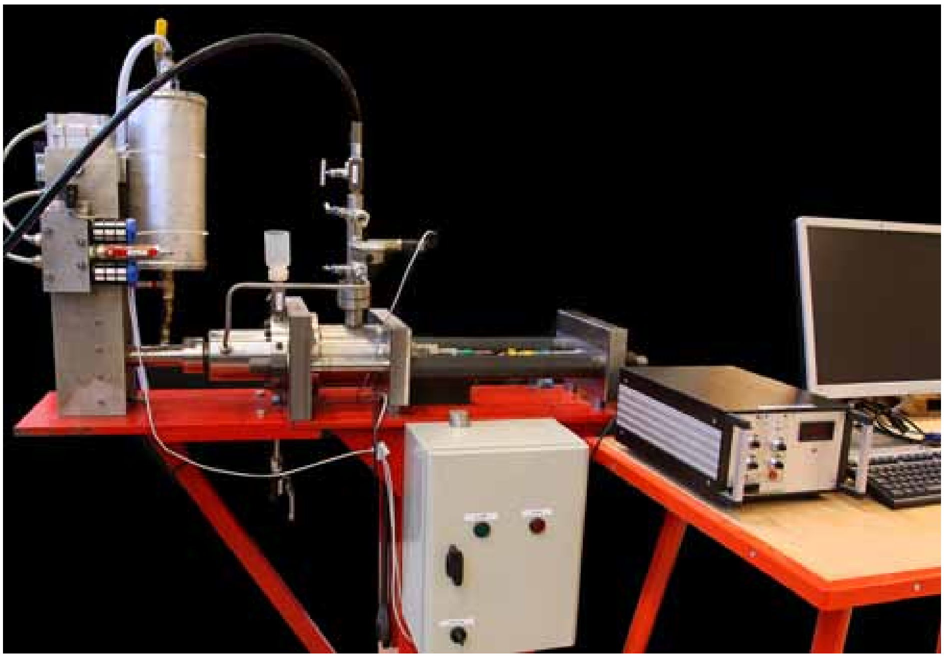


Figure 30 – Hydro-pneumatic machine.
Photo: Melinda Gaal.

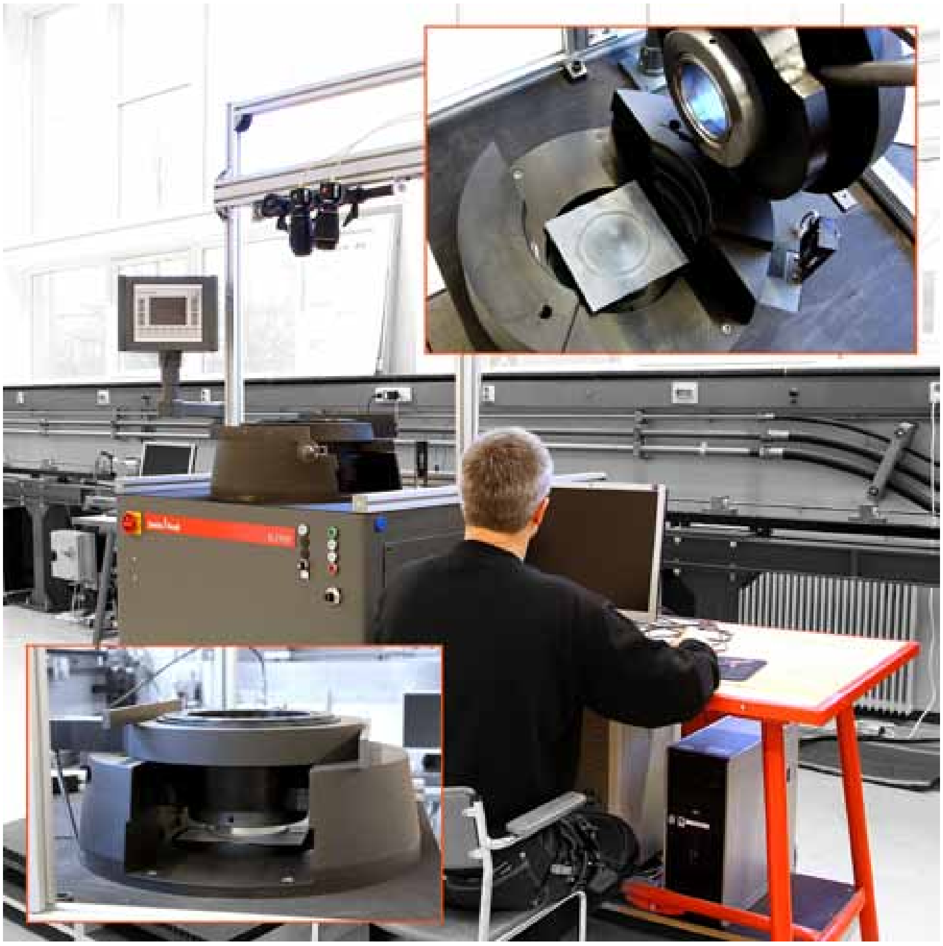


Figure 31 – BUP 600 machine. *Photo: Melinda Gaal.*

The machine has been equipped with a pair of high resolution black and white Prosilica cameras GC2450, with a resolution of 2448x2050 pixels, and a frame rate of 15 fps at full resolution. The cameras are PC-controlled by software for image acquisition. A frame has been built on the machine that allows easy positioning of the cameras and image acquisition during testing, thereby providing the opportunity for strain field measurement on the upper surface of the test pieces.

FOR MORE INFORMATION:
Lademo O-G, Engler O, Keller S, Berstad T, Pedersen KO, Hopperstad OS: *Identification and validation of constitutive model and fracture criterion for AlMgSi alloy with application to sheet forming,* Materials & Design 2009; 30: 3005-3019.

Component and structural testing

Pendulum accelerator ("Kicking machine")
The pendulum accelerator is a device for impact testing of components and structures, see Figure 32. Basically, the test rig accelerates a trolley on rails towards a

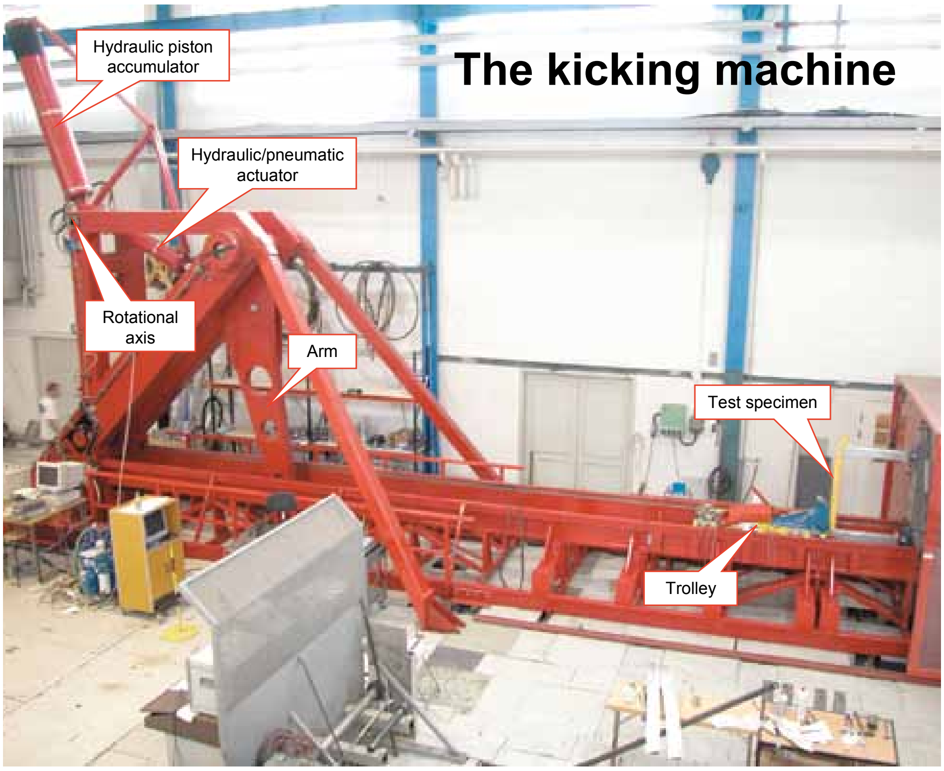


Figure 32 – Pendulum accelerator.

test specimen fixed to a reaction wall. The accelerating system consists of an arm that rotates around a set of bearings. The arm itself is connected to a hydraulic/pneumatic actuator system which provides the moving force and accelerates the trolley up to the desired velocity. The connection of the actuator piston rod to the arm introduces a 1.5 lever action, i.e. the force acting on the trolley is 1/5 of the piston force, but the velocity is 5 times greater. Based on the maximum working pressure in the hydraulic piston, the maximum energy delivered to the trolley is approximately 500 kJ. At present the mass of the trolley is in the range between 400 and 1500 kg, giving a maximum velocity between 50m/s and 26m/s which is measured with a photocell system. In case the specimen does not have sufficient energy absorption capability to stop the trolley, a secondary energy absorbing system is installed.

During testing the trolley and the reaction wall can be equipped with a load cells where for each the axial force as well as two orthogonal bending moments can be recorded. The deformations of the specimen during testing can be recorded with two simultaneously working high-speed cameras.

FOR MORE INFORMATION:
Hanssen A.G., Auestad T., Tryland T. and Langseth M.: *The Kicking machine: A device for impact testing of structural components.* IJCrash 2003 Vol. 8 No. 4 pp. 385-392.

Pneumatic accelerator

In this test rig, see Figure 33, a projectile with a mass in the range 20-50 kg can be accelerated up to velocities between 25m/s and 40m/s. The rig consists of an accelerator tube (with an internal diameter of 160mm) which is connected to a compressed air chamber at the top and a projectile which is designed to act as a piston inside the accelerator tube during testing. The projectile consists of a central rod, a replaceable nose and is equipped with guides and an interchangeable mass.

During testing the interface force between the projectile and target is measured with strain gauges. After integrating the force signal twice, the force vs. displacement time curve is obtained. The test rig has been used to study the behaviour of plated structures subjected to large mass projectiles in the low velocity regime as well as the behaviour of aluminium tubes under axial compression.

FOR MORE INFORMATION:
Langseth M. and Larsen P.K.: *Dropped Objects' Plugging Capacity of Steel Plates:* An Experimental Investigation. International Journal of Impact Engineering 9 (1990) 289–316.

Compressed gas gun

A compressed gas gun for ballistic impact studies is also available at SIMLab. A schematic drawing of the facility is shown in Figure 34. The main components of the gas gun are the 200 bar pressure tank, the purpose-built firing unit for compressed gas, the 10 m long smooth barrel of calibre 50 mm and the closed 16 m^3 impact chamber. Due to the size of the impact chamber, large structural component may be full-scale tested. The gas gun is designed to launch a 250 g projectile/sabot package to a maximum velocity of 1000 m/s when helium is used as propellant. The projectile is mounted in a sabot, allowing a variety of striker geometries and masses to be used, and the package is inserted into the rear end of the barrel. When the package leaves the muzzle, the sabot is immediately separated from the projectile due to aerodynamic forces. A sabot trap allows the projectile to pass freely while the sabot parts are stopped. The projectile passes the initial velocity measurement station before it impacts the clamped target after about 2 m of free flight. To allow high-speed photography during impact, the clamping system is equipped with a framing window. If the projectile perforates the target, residual velocities are measured before all free flying bodies are stopped without further damage in a rag-box. After testing, the impact chamber may be opened for final inspections and measurements.

Figure 33 – Pneumatic accelerator.

Photo: Melinda Gaal.

FOR MORE INFORMATION:

Børvik T, Langseth M, Hopperstad OS, Malo KA. *Ballistic penetration of steel plates.* International Journal of Impact Engineering 1999;22:855-886.

Børvik T, Hopperstad OS, Langseth M, Malo KA. Effect of target thickness in blunt projectile penetration of Weldox 460 E steel plates. International Journal of Impact Engineering 2003;28:413-464.

Stretch-bending rig

The stretch-bending rig, see Figure 35, applies a combined bending and axial tensile/compressive loading to the test component. The length of the specimens is 1-2 m, and they are bent around an exchangeable die with a defined curvature. The main components of the test rig are a rigid steel frame, two horizontally mounted servohydraulic actuators giving the axial action, and a vertical loading device supported on a servohydraulic actuator. All actuators have a capacity of 330 kN. The rig has a complete instrumenttion including load cells, displacement transducers and clinometers. Cameras may also be attached. It can be operated in force as well as displacement control, and a broad variety of loading sequences may thus be defined.

The rig has been employed in tests where the bending operation of car bumpers is studied. It has also been used to simulate pipelaying and in formability tests exploring the onset and propagation of fracture.

FOR MORE INFORMATION:

Clausen A.H., Hopperstad O.S. and Langseth M.: *Strech bending rig. Experimental set-up.* Report R-9-96 (Revised 1999). Department of Structural Engineering, NTNU.

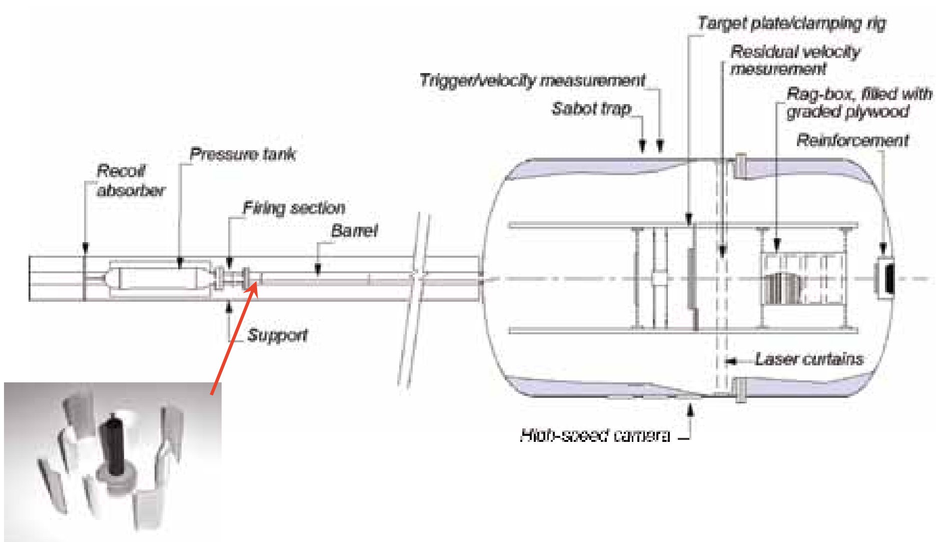


Figure 34 – Schematic drawing of the gas-gun facility.

Joining machine

Self-piercing riveting machine

In this machine, see Figure 36, self-piercing riveting can be carried out of sheets under industrial conditions. The machine has been purchased from Böllhoff in Germany.

FOR MORE INFORMATION:
www.boellhoff.com/en/de/assembly_systems/riveting/rivset.php

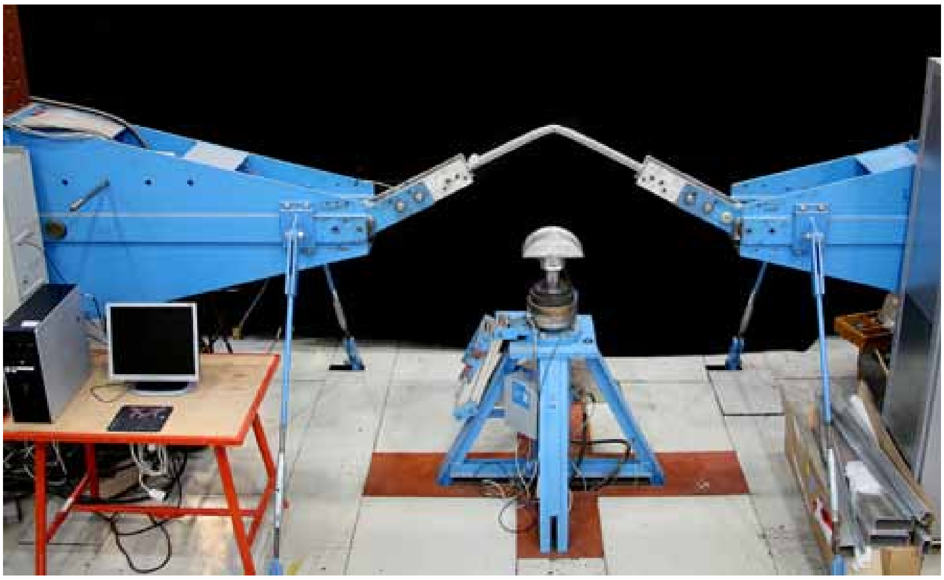


Figure 35 – Stretch-bending rig. Photo: Melinda Gaal.

Figure 36 – Self-piercing riveting machine. Photo: Melinda Gaal.

Evaluation of the research carried out at the Centre

The Scientific Advisory Board meeting was held in Neckarsulm 4 November 2009.
A mandate was defined were the board was asked to evaluate:

- The research carried out with respect to the defined objective for the Centre
- Relevance of the research with respect to the industrial and public partners
- Scientific quality

Main conclusions from the evaluation

The Scientific Advisory Board concluded that the CRI-SIMLab has achieved a high international visibility which is shown by the increasing number of visitors, their excellent publication record and other indicators, such as being the first European research group invited to join the "Lightweight Blast Resistant Structural Group" in the US. They have a strong identity which is characterized by their successful integration of theoretical developments and laboratory investigations into finely focused studies. The CRI has achieved excellent cooperation with the partners who recognize the uniqueness of this research group. The basic studies undertaken in the lightweight structures field will be of value for many industries in the years ahead, as new material models are developed, and the illustrations of their applications through the demonstrators will broadcast to industry how their basic work can be applied to many future industrial applications.

The board would like to stress the limited number of NTNU staff in the CRI (2 man-years) for such an important task and that NTNU, in order to maintain and improve the quality of the group, should engage extra assistance and more human resources. Furthermore, during the meeting in Neckarsulm, it was observed by the board that the partners were very comfortable with the structure of the CRI as it works now and the type of interactions it is providing between them. This structure is already quite involved for the group, so that the implementation of other large programmes, such as European programmes, might be harmful for the research output and development of the group, despite other potential benefits. The CRI could, however, act as a partner (and not a leader) in such a framework

The board is unanimous in congratulating Professor Magnus Langseth for assembling an outstanding team, and in encouraging and sustaining excellent interaction between the team members and the industrial partners. The outstanding outcome of the third year of the CRI bodes well for the remaining five years of the eight-year programme.

Concurrent research projects

The following selection of research projects have been run in 2009 utilizing the competence developed at the Centre:

- *EU project:* NTNU and SINTEF were involved in an EU project called NADIA for the period 2006-2009. The project dealt with new automotive components designed for and manufactured by intelligent processing of light alloys based on aluminium and magnesium. The NADIA project had 24 partners.

- *PhD project:* Heidi Moe defended her PhD thesis at SIMLab on 26 March 2009. The PhD project was funded by the Research Council of Norway through the Intelli-STRUCT programme (Intelligent Structures in Fisheries and Aquaculture) at SINTEF Fisheries and Aquaculture. The main goal of this PhD project was to develop a method for non-linear strength analysis of net structures applied in the aquaculture and fishing industries. The work focused on the aquaculture net cage, and included research to establish knowledge within material properties and failure modes of traditional netting materials for aquaculture.

- *Crash systems in trucks (2009-2011):* SIMLab is together with Kongsberg Automotive and SINTEF Raufoss Manufacturing involved in a user-defined research project (BIP project) funded by the Research Council of Norway. The activity at SIMLab is related to a PhD candidate (Espen Myklebust) who will work on robust design of crash systems related to geometry and material variations.

- *Duplex pipe fittings with sigma phase precipitation (2009):* SIMLab in cooperation with SINTEF has been involved in a project for Statoil to evaluate the impact resistant of duplex pipe fittings with sigma-phase precipitates. Material tests at elevated rates of strain and component impact tests in the SIMLab's pendulum accelerator have been carried out.

- *JIP CO2PIPETRANS:* SINTEF has been involved in the JIP led by DNV for the period 2008-2009. The main objective of this project was to establish a Recommended Practice for development, design, construction, testing, operation and maintenance of steel pipelines for the transmission of CO2 in dense, high pressure phase. SINTEF has evaluated the applicability of using numerical tools for the prediction of running ductile fracture.

- *FME BIGCCS (2009-2016):* In the research task CO2 Pipeline Integrity, the main objective is to develop a coupled fluid-structure model to enable safe and cost-effective design and operation of CO2 pipelines. Further, requirements to avoid running ductile fracture in pipelines pressurized with CO2 and CO2 mixtures will be established.

- *FME Centre for Solar Cell Technology (2009-2017):* The overall objective is to give current and future companies in the Norwegian PV industry long-term access to world leading technological and scientific expertise.

- *BIP NextGenSi:* SINTEF, NTNU and TU Bergakademie Freiberg together with 3 PV-related companies are involved in this BIP for the period 2009-2013. The main objective of the project is to develop technologies for next generation production line equipment for ultra-thin silicon wafers. A modelling activity is working on assessing and understanding the effects of selected parameters on wafer life in the production chain.

- *KMB COMPACT (2009–2013):* This project is based on collaboration with the research group 'Polymers and composites' at SINTEF Materials and Chemistry, and other industries than those that are involved in the Centre. There is close analogy to the activities at the Centre as this project will develop design tools for composite structures on advance continuous fibre polymer composites.

EU applications

Any EU application with involvement from the partners has been discussed by the Board, but so far there is no enthusiasm with respect to such an initiative from the majority of the industrial partners. The experience the international partners have from previous EU projects is that the CRI-concept is a much better model in order to obtain a generic technical focus where theory and applications are strongly linked. Thus the strategy in 2009 has been not to take any initiative for such an application, but rather try to be involved in applications where the initiative is coming from outside the consortium. This is also in accordance with the advice from the Scientific Advisory Board. With this in mind, the Centre has been involved in

- *The Green Car Initiative* within the 7th framework programme together with the Université de Valenciennes et du Hainaut-Cambrésis in France. The idea behind the initiative is to look at the crashworthiness of a small battery-driven city car.
- A proposal within the 7th framework programme on *Composite Materials under Dynamic Extreme Loading (CoDEx)*. The co-ordinator of the programme is Cranfield University, UK.
- A Cost proposal on the *Dynamic Testing for Materials and Structures Research*. The research network covers totally 21 universities and research organizations. The coordinator of the proposal is the University of Applied Sciences of Southern Switzerland. The proposal did not pass the evaluation round, but will be modified and re-submitted in 2010.

New equipment

- *New reaction wall for the SIMLab pendulum accelerator:* A reaction wall has been designed and will be installed spring 2010. The new reaction wall will have a total weight of 130 000 kg and will be floating on the floor by using special-purpose designed shock absorbers. This will limit the transfer of dynamic forces to the laboratory floor and thus the rest of the building

International seminar

- The Centre organized a workshop on 10-11 June 2009 on the behaviour and modelling of polymers. The seminar gathered 20 scientists from Norway, USA, UK, France, Switzerland and Germany. Based on advice from the Scientific Advisory Board in 2008, the seminar was organized to strengthen the testing and modelling activity on polymers in the Centre.

Visibility

Awards

- Professor Magnus Langseth has been awarded the title of "Docteur Honoris Causa" at the Université de Valenciennes et du Hainaut-Cambrésis in September 2009
- Professor Øystein Grong was awarded the NTNU and SINTEF technological prize for 2009. He was also awarded the Cook/Ablett-prize for 2009 by the Institute of Minerals & Mining, UK

CISIT – Valenciennes, France

- Professor Magnus Langseth is a member of the International Scientific Advisory Committee for the International Campus on safety and Intermodality in Transportation (CISIT) at Valenciennes, France. CISIT is an eight-year programme ending 2013 which covers design and optimal management of the multimodal chain for freight or passenger transportation, human and technical safety and engineering for integrated design of vehicle and intelligent infrastructures.

Keynote lectures

- Professor Magnus Langseth has given three keynote lectures in 2009, i.e.
  1) at the 7th LS-DYNA Conference on 14-15 May 2009 in Salzburg, Austria
  2) at the Integrity Reliability and Failure conference on 20-24 July 2009 in Porto, Portugal and
  3) at the COBEM2009 conference on 15-20 November 2009 in Gramado, Brazil.

Guest lectures

- Professor Arild Clausen gave a guest lecture at Laboratoire de Mécanique et Technologie, Ecole Normale Superieure de Cachan, 5 November 2009 on the topic *"On constitutive modelling of thermoplastics"*.
- Professor Clausen visited the Group of Solid Mechanics and Structural Impact, University of São Paulo, Brazil on 23 November 2009 where he gave a guest lecture on the topic *"Modelling of thermoplastics - Tests and numerical simulations"*.

Magazines/Newspapers

- An article related to safety barriers was presented in the magazine Gemini, autumn 2009. Behaviour and modelling safety barriers is the topic of the PhD thesis of Henning Fransplass. The same article was published in Norway's largest newspaper VG, 24 February 2009.

Workshop on behaviour and modelling of polymers.


Virtual car crashes

Virtual testing of safety barriers will save Norway a great deal of money – and will mean fewer injured and killed in traffic accidents.


SMADRER

virtuelle autovern hver dag

Henning Fransplass vil spare menneskeliv. Derfor smadrer han biler og autovern hver eneste dag.

National cooperation

The Centre has established cooperation with Assoc. Professor Ørjan Fyllingen at the Bergen University College. He holds a PhD from the Department of Stuctural Engineering, NTNU, and has specialized on how parameter variations can be taken into account in numerical simulations to predict a robust behaviour of structures subjected to impact. Ørjan Fyllingen is a co-supervisor for one of our PhD candidates.

International cooperation and agreements

Research

The Centre has strong international cooperation due to three international partners, i.e. Audi, Renault and SSAB Swedish Steel. In addition SIMLab has in 2009 had the following international research cooperation:

- *LMT-Cachan, France*
  – Professor Ahmed Benallal has stayed six months at the Centre in 2009 as a part of his one year sabbatical. His research contribution is related to the experimental identification and modelling of the Protevin-Le Châtelier (PLC) effect.
  - Professor Arild Clausen from SIMLab had a two month stay at this laboratory in October – December 2009. His cooperation with LMT-Cachan and in particular with professor Ahmed Benallal and his PhD candidate Rodrigo Nogueira de Codes has been related to thermo-mechanical properties and biaxial testing of polymers.
  - Common journal publications have been worked out.
- *University of São Paulo, Brazil*
  – Professor Marcilio Alves had a two week stay at the Centre in September. The research cooperation is related to the behaviour and modelling of polymers. One of his PhD candidates had a two month stay at the Centre in autumn 2009. Common publications are worked out.
- *MIT, USA*
  – The cooperation with Professor Tomasz Wierzbicki has resulted in a common publication on perforation with fragment formation which was presented at the IUTAM conference in Austin Texas, USA.
- *University of Savoie, France*
  – Cooperation has been established between SIMLab and SYMME at the University of Savoie related to 1) thermo-mechanical modelling and measurements and 2) fundamentals of work-hardening and crystal plasticity. A common journal publication has been worked out.
- *Politecnico di Milano, Italy*
  – Professor Andrea Manes had a six month stay at SIMLab in 2008/2009 where he worked on modelling of pipelines subjected to impact loading conditions. The work has been presented at the Computational methods in Marine Engineering conference in Trondheim in June 2009.
- *University of Linköping, Sweden*
  – The well established cooperation with Professor Larsgunnar Nilsson and his PhD candidate David Lönn has resulted in a common publication on robust design methods for automotive structures.
- *MURI project*
  – The University of California at Santa Barbara (UCSB) in cooperation with Havard University, University of Virginia, MIT and University of Cambridge have established a Multidisciplinary University Research Initiative Project (MURI) titled An Integrated Cellular Materials Approach to Force Protection and sponsored by the U.S. Navy. A common research activity on blast loading and response of aluminium panels has been established in 2009.
- *Dr Michael Forrestal and Dr Thomas Warren (USA):*
  – The cooperation with Dr Forrestal and Dr Warren on behaviour and analytical modeling of targets subjected to projectile impact has resulted in common publications in 2009.
- *Impetus Afea AB, Sweden*
  – Strong cooperation has been established with Dr Lars Olovsson on the modeling of self-piercing rivets as well as on blast loading of flexible structures using a particle-based method. Common publications have been worked out.
- *DYNALAB, Italy*
  - A common publication with Dr Carlo Albertini has been worked out on the Hydro-pneumatic machine and presented at the DYMAT2009 conference.

Guest lectures

The following guest lectures have been given at SIMLab in 2009:

- Professor Marcilio Alves, University of São Paulo, Brazil: *Structural Impact and Material Failure.*
- Professor Sylvi Pommier, LMT-Cachan: *Fatigue crack growth under complex loading conditions.*
- Dr Charles E. Anderson, Southwest Research Institute, USA: *Impact of Short and Long Rods into Glass Targets.*
- Dr Timothy Holmquist, Southwest Research Institute, USA: *Material Modelling and Numerical Algorithms and Computed Results for High Velocity Impact*
- Professor Karl Schweizerhof, University of Karlsruhe, Germany: *On Low Order "Solid Shell" Elements for Large Deformation Problems – Merits and Limits.*
- Professor Lili Wang, Ningbo University, Ningbo, China: *Shear failure and adiabatic shearing under high strain rates.*
- Professor Fenghua Zhou, Ningbo University, Ningbo, China: *Numeric study on the rate dependent dynamic fragmentation.*
- Dr Graham Schleyer, University of Liverpool, UK: *Blast and impact resistance of ultra high performance fibre reinforced concrete beams and slabs.*

Agreements

The Department of Structural Engineering at the Norwegian University of Science and Technology (NTNU) has closely cooperated with Livermore Software Technology Cooperation (LSTC) during the last twenty years on the development of material models in LS-DYNA. An agreement has been signed in 2009 in order to formalize these cooperative efforts under the SIMLab umbrella. It addresses how SIMLab and LSTC will cooperate in the future with regard to SIMLab's licensing and use of LS-DYNA, SIMLab's access to LS-DYNA source code, and how the models developed at SIMLab will be made available to LSTC.

Recruitment

PhD candidates, post docs and visiting students from Denmark, France, Germany, Malaysia, Norway, Syria, USA and Vietnam. *Photo: Melinda Gaal.*

PhD candidates

The following PhD candidates were linked to the Centre in 2009:

NAME	START	PLANNED EXAM	PROGRAMME	CITIZENSHIP	MALE/FEMALE
Ida Westermann*	Autumn 2007	Autumn 2010	M^4	Denmark	Female
Henning Fransplass*	Spring 2005	Spring 2011	OptiPro	Norway	Male
Virgile Delhaye*	Summer 2007	Autumn 2010	Polymers	France	Male
Egil Fagerholt*	Winter 2008	Winter 2011	F&CP	Norway	Male
Nguyen-Hieu Hoang*	Autumn 2007	Autumn 2010	C&J	Vietnam	Male
Gaute Gruben*	Summer 2008	Summer 2012	F&CP	Norway	Male
Anne S. Ognedal*	Autumn 2008	Autumn 2012	Polymers	Norway	Female
Octavian Knoll*	Winter 2009	Winter 2012	F&CP	Germany	Male
Marion Formeau**	Autumn 2009	Autumn 2012	F&CP	France	Female
Knut Rakvåg**	Summer 2009	Summer 2013	OptiPro	Norway	Male
A.B. Alisibramulisi**	Autumn 2007	Autumn 2010	M^4	Malaysia	Female

*= Salary and operational cost from the Centre,
** = Operational cost from the Centre only – salary from other sources

New PhD candidates in 2009

- Marion Fourmeau has a master's degree from LMT-Cachan in Paris and has been employed as a PhD candidate from September 2009 at SIMLab. Based on her excellent marks she was offered a position financed by the Faculty of Engineering Science and Technology (IVT). However, the operational costs are covered by the Centre. She has supervisors from both NTNU and LMT-Cachan and the cooperation between the two universities is regulated through a cotutelle agreement.
- Knut Rakvåg had also excellent marks from his master's study and was thus recruited as a PhD candidate with financial support from the IVT-faculty. The Centre covers the operational costs
- Octavian Knoll is a PhD candidate at the University of Karlsruhe in Germany and his salary is covered by Audi as a part of their contribution in kind. However, the link the candidate will have with NTNU is regulated through a cotutelle agreement between NTNU and the University of Karlsruhe.

Affiliated PhD candidates in 2009

- Espen Myklebust is employed as a PhD candidate at the Department of Structural Engineering and linked to a BIP project on robust design of crash systems in trucks. The coordinator of the project is Kongsberg Automotive. Espen Myklebust is affiliated with the SIMLab group and utilises the available infrastructure.
- Andreas Koukal is a PhD candidate at the Technische Universität München. He was recruited by Audi to work on behaviour and modelling of polymers and is affiliated to the Centre.

Excursion

In order to strengthen future recruitment of Norwegian PhD candidates a trip with 21 of our master's students to Hydro Aluminium Sunndaløra was organised 21-22 October 2009. Hydro Aluminium gave a presentation before the guided tour to the production plant and emphasized the need to recruit scientists with a PhD background.

Equal opportunity

In the application we have planned to have at least 30% female PhD candidates. At present four of the eleven PhD candidates are female, i.e. 36%.

Post docs

The following post docs were linked to the Centre in 2009:

NAME	START	END	PROGRAMME	CITIZENSHIP	MALE/FEMALE
Venkatapathi Tarigopula**	Summer 2007	Summer 2009	F&CP + OptiPro	India	Male
Afaf Saai	Autumn 2009	Autumn 2011	M^4	Syria	Female

** Dr Tarigopula is now employed by Det Norske Veritas

Visiting students and post docs

The following international students have stayed at the Centre in 2009:

- Master's student *Mickaël Guérineau* from Ecole Centrale de Nantes, France stayed at the Centre for five months during his internship. He was linked to the Polymers programme.
- Master's student *Francois Brugier* from Ecole Normale Supérieure de Cachan, France stayed at the Centre for four months during his internship. He was linked to the OptiPro programme.
- PhD student *Rafael Traldi Moura* from the University of São Paulo, Brazil stayed at the Centre for two months working on the behaviour and modelling of polymers, i.e. he was linked to the Polymer programme.
- Post doc *Xinke Xiao* from Harbin Institute of Technology in China stayed at the Centre for six months in 2008/2009 working on the OptiPro programme.
- Master's student *John Werner* from University of Washington, USA stayed at the Centre for six months in 2009/2010 working on the OptiPro programme with impact on submerged pipelines.

Master's students

The following Master's students were linked to the Centre in spring 2009:

STUDENT	TOPIC
Christian Berg	Computer implementation of the element method for crack growth problems
Anders Tørres Bøksle	Deformation of polymers: Tests and numerical simulation
Anders Kildahl Forseth	Investigation of cylindrical steel pipes with standardized pile ends
Gunnar Wirum Granum	Nonlinear analyses of rectangular hollow section joints
Magne Hovde	Plate girders with large web openings
Torstein Kjøs Johansen	Fracture of ductile materials: Experiments and simulations
Arne Øyvind Kolstrøm	Beam to column joints
Erik Christoffer Langmoen	Behaviour of long aluminium extrusions subjected to axial loading
Anders Lervik	Beam to column joints
Ole Johnny Lyng	Beam to column joints
Espen Myklebust	Crash systems in trucks
Per Didrik Nonstad	Imperfections in steel girders with web openings
Martin Reutz Nøttveit	Low velocity perforation of steel plates
Knut Gaarder Rakvåg	Combined blast and fragment loading of plates
Christian Revå	Computer implementation of the element method for crack growth problems
Audun Trøite Sandven	Blast loaded window glasses
Lars Worren	Capacity of beam girders loaded in shear

Annual accounts

The annual work plans for each research programme have to present a detailed description of the activities to be carried out in the Centre, allowing the Research Council of Norway (RCN) to monitor that that the research activities are within the ESA requirements. Thus the funding plan for each programme shows the funding from each of the partners in the form of "Fundamental research (F)" and "Industrial research (I)" and how funding from the Research Council of Norway contributes to funding of each project. The cost plan describes each partner's participation in each of the programmes. The funding and cost plans for 2009 are shown below.

SIMLab: Funding 2009 (All figures in 1000 NOK)

		STATE AID			INDUSTRY									
Research Programme	Type of research	RCN Grant	Host (NTNU)	SINTEF	NDEA	NPRA	AUDI	Renault	Statoil	SSAB	Hydro Aluminium	Total State Aid	Total Funding	State aid/total funding
C&J	F	1708	112			870					150	1820	2840	0.64
C&J	I													
F&CP	F	2058	1273		300		500				350	3331	4481	0.74
F&CP	I													
M^4	F	1093	1384	1100							180	3577	3757	0.95
M^4	I										2167		2167	0
OptiPro	F	1553	187		1825					600		1740	4165	0.42
OptiPro	I													
Poly	F	1808	1112					500	100			2920	3520	0.83
Poly	I													
Demo	F													
Demo	I	249	112		75						433	361	869	0.42
Equipment											600		600	
Adm		1873	820			250	500	500	550	200	220	2693	4913	
Total		**10342**	**5000**	**1100**	**2200**	**1120**	**1000**	**1000**	**650**	**800**	**4100**	**16442**	**27312**	

F = Fundamental research
I = Industrial research

RCN = Research Council of Norway
NDEA = Norwegian Defence Estates Agency
NPRA = Norwegian Public Roads Administration

SIMLab: Cost 2009 (All figures in 1000 NOK)

Research Programmes	Host (NTNU)	SINTEF	NDEA	NPRA	AUDI	Renault	Statoil	SSAB	Hydro Aluminium	Total
C&J	1470	500		870						2840
F&CP	2431	1350	200		500					4481
M^4	2182	1575							2167	5924
OptiPro	1765	1100	1000					300		4165
Poly	1970	1050				500				3520
Demo	161	275							433	869
Equipment	600									600
Adm	2963	1950								4913
Total	**13542**	**7800**	**1200**	**870**	**500**	**500**		**300**	**2600**	**27312**

Publications

The following lists journal publications and conference contributions generated within the Centre in 2009.

Journal publications - Published articles

1. Achani D, Hopperstad OS, Lademo O-G: *Behaviour of extruded aluminium alloys under proportional and non-proportional strain paths.* Journal of Materials Processing Technology 2009; 209: 4750-4764.
2. Alsos H, Amdahl J, Hopperstad OS: *On the resistance to penetration of stiffened plates, Part II: Numerical analysis*. International Journal of Impact Engineering 2009; 36: 875-887.
3. Børvik T, Forrestal MJ, Hopperstad OS, Warren TL, Langseth M: *Perforation of AA5083-H116 aluminium plates with conical-nose steel projectiles – Calculations.* International Journal of Impact Engineering 2009;36: 426-437.
4. Børvik T, Dey S, Clausen AH: *Perforation resistance of five different high-strength steel plates subjected to small-arms projectiles.* International Journal of Impact Engineering 2009; 36: 948-964.
5. Børvik T, Hanssen AG, Langseth M, Olovsson L: *Response of structures to planar blast loads – A finite element engineering approach.* Computers & Structures 2009; 87: 507-520.
6. Chen Y, Clausen AH, Hopperstad OS, Langseth M: *Stress-strain behaviour of aluminium alloys at a wide range of strain rates.* International Journal of Solids and Structures 2009; 46: 3825-3835.
7. Chen Y, Pedersen KO, Clausen AH, Hopperstad OS, Langseth M: *An experimental study on the dynamic fracture of extruded AA6xxx and AA7xxx aluminium alloys.* Materials Science and Engineering A 2009; 523: 253-262.
8. Dumoulin S, Hopperstad OS, Berstad T: *Investigation of integration algorithms for rate-dependent crystal plasticity using explicit finite element codes.* Computational Materials Science 2009; 46: 785-799.
9. Dørum C, Laukli HI, Hopperstad OS: *Through-process numerical simulations of the structural behaviour of Al–Si die-castings.* Computational Materials Science 2009; 46: 100-111.
10. Dørum C, Hopperstad OS, Berstad T, Dispinar D: *Numerical modelling of magnesium die-castings using stochastic fracture parameters.* Engineering Fracture Mechanics 2009; 76: 2232-2248.
11. Dørum C, Laukli HI, Hopperstad OS, Langseth M: *Structural behaviour of Al-Si die-castings: Experiments and numerical simulations.* European Journal of Mechanics, A/Solids 2009; 28: 1-13.
12. Dørum C, Dispinar D, Hopperstad OS, Berstad T: *A probabilistic approach for modelling of fracture in magnesium die-castings.* Metallurgia Italiana 2009; 51-54.
13. Fyllingen Ø, Hopperstad OS, Lademo O-G, Langseth M: *Estimation of forming limit diagrams by the use of the finite element method and Monte Carlo simulation.* Computers and Structures 2009; 87: 128-139.
14. Fyllingen Ø, Hopperstad OS, Langseth M: *Robustness study on the behaviour of top-hat thin-walled high-strength steel sections subjected to axial crushing.* International Journal Impact Eng 2009; 36: 12-24.
15. Grytten F, Børvik T, Hopperstad OS, Langseth M: *Quasi-static perforation of thin aluminium plates.* International Journal of Impact Engineering 2009; 36: 486-497.
16. Grytten F, Børvik T, Hopperstad OS, Langseth M: *Low velocity perforation of AA5083-H116 aluminium plates.* International Journal of Impact Engineering 2009; 36: 597-610.
17. Kane A, Børvik T, Hopperstad OS, Langseth M: *Finite element analysis of plugging failure in steel plates struck by blunt projectiles.* Journal of Applied Mechanics 2009; 76:1-11.
18. Lademo O-G, Engler O, Keller S, Berstad T, Pedersen KO, Hopperstad OS: *Identification and validation of constitutive model and fracture criterion for AlMgSi alloy with application to sheet forming,* Materials & Design 2009; 30: 3005-3019.
19. Lilleby A, Grong Ø, Hemmer H, Erlien T: *Experimental and finite element studies of the divergent extrusion process under conditions applicable to cold pressure welding of commercial purity aluminium.* Materials Science and Engineering A 2009; 518: 76-83.
20. Lilleby A, Grong Ø, Hemmer H: *Experimental and finite element simulations of cold pressure welding of aluminium by divergent extrusion.* Materials Science and Engineering A 2009; 527: 179-186.
21. Lou DC, Solberg JK, Børvik T: *Surface strengthening using a self-protective diffusion paste and its application for ballistic protection of steel plates.* Materials & Design 2009; 30: 3525-3536.
22. Moe H, Hopperstad OS, Olsen A, Jensen O, Fredheim A: *Temporary-creep and post-creep properties of aquaculture netting materials.* Ocean Engineering 2009; 36: 992-1002.
23. Moe H, Gaarder RH, Olsen A, Hopperstad OS: *Resistance of aquaculture net cage materials to biting by Atlantic Cod (Gadus morhua).* Aquacultural Engineering 2009; 40: 126-134.
24. Mousavi MG, Cross CE, Grong Ø: *The effect of high temperature eutectic forming impurities on aluminium 7108 weldability.* Welding Journal 2009; 88: 104-110.
25. Myhr OR, Grong Ø: *A novel modelling approach to the optimisation of welding conditions and heat treatment schedules for age hardening aluminium alloys.* Science and Technology of Welding and Joining 2009; 14: 321-332.
26. Myhr OR, Grong Ø, Lademo O-G, Tryland T: *Optimising crash resistance of welded aluminium structures.* Welding Journal 2009; 88: 42-45.
27. Reyes A, Eriksson M, Lademo O-G, Hopperstad OS, Langseth M. *Assessment of yield and fracture criteria using shear and bending tests.* Materials and Design 2009; 30: 596-608.
28. Tarigopula V, Hopperstad OS, Langseth M, Clausen AH: *An evaluation of a combined isotropic-kinematic hardening model for representation of complex strain-path changes in dual-phase steel.* European Journal of Mechanics A/S Solids 2009; 28: 792-805.
29. Westermann I, Hopperstad OS, Marthinsen K, Holmedal B: *Ageing and work-hardening behaviour of a commercial AA7108 aluminium alloy.* Materials Science and Engineering A 2009; 524: 151-157.
30. Hagen NC, Larsen PK; Aalberg A: *Shear capacity of steel platre girders with large web openings, Par I: Modeling and simulations.* Journal of Constructional Steel Research 2009; 65: 142-150
31. Hagen NC, Larsen PK: *Shear capacity of steel plate girders with large web openings, Part II: Design guidelines.* Journal of Constructional Steel Research 2009; 65: 151-158.

Keynote lectures

1. Langseth M: C*rashworthiness of Aluminium Structures. Modelling and Validation.* Keynote lecture at the 7th European LS-DYNA Conference, Salzburg, Austria, 14-15 May 2009.
2. Langseth M: *Crashworthiness of Aluminium Structures.* Keynote lecture at IRF'2009 Conference, Porto, Portugal, 20-24 July 2009.

3. Langseth M: *Advances in Solid Mechanics: Crashworthiness of Aluminium Structures, Modelling and Validation.* Keynote lecture at COBEM 2009, Gramado, RS, Brazil, 15-20 November 2009.

Oral presentations at conferences

1. Berstad T, Dørum C, Hopperstad OS, Børvik T: *Simulation of Crack Propagation using Damage-Driven Fission Adaptivity Coupled with Element Erosion or Node Splitting.* Presented at the 7th European LS-DYNA Conference, Salzburg, Austria, 14-15 May 2009.
2. Børvik T, Aunehaugen H, Hopperstad OS: *Impact behaviour of the high-strength aluminium alloy AA7075-T651.* Presented at 9th International Conference on the Mechanical and Physical behaviour of Materials under Dynamic Loading (DYMAT 2009), Brussels, Belgium, 7-11 September 2009.
3. Clausen AH, Moura RT, Alves M, Langseth M, Polanco-Loria M, Berstad T, Hopperstad OS: *Impact of PEHD plates: Experimental tests and numerical simulations.* Presented at 20th International Congress of Mechanical Engineering (COBEM 2009), Gramado, Brazil, 15-20 November 2009.
4. Clausen AH, Polanco-Loria M, Moura RT, Alves M, Berstad T, Langseth M, Hopperstad OS: *Polymer plates subjected to impact: Experimental tests and numerical simulations.* Presented at the 9th International Conference on the Mechanical and Physical behaviour of Materials under Dynamic Loading (DYMAT 2009), Brussels, Belgium, 7-11 September 2009.
5. Polanco-Loria M, Clausen AH, Berstad T, Hopperstad OS: *A Constitutive Model for Thermoplastics Intended for Structural Applications.* Presented at the 7th European LS-DYNA Conference, Salzburg, Austria, 14-15 May 2009.
6. Fyllingen Ø, Hopperstad OS, Hanssen AG, Langseth M: B*rick versus shell elements in simulations of aluminium extrusions subjected to axial crushing.* Precented at the 7th European LS-DYNA Conference, Salzburg, Austria, 14-15 May 2009.
7. Manes A, Porcaro R, Børvik T, Langseth M, Ilstad H: *Calibration of a constitutive material model for sub-sea pipelines.* Presented at Computational Methods in Marine Engineering (Marine 2009), Trondheim, Norway, 15-17 June 2009.
8. Moura RT, Clausen AH, Langseth M, Alves M: *Dispersion and inertia effects analysis on dynamic mechanical material characterization.* Presented at the 20th International Congress of Mechanical Engineering (COBEM 2009), Gramado, RS, Brazil, 15-20 November 2009.
9. Tarigopula V, Hopperstad OS, Langseth M, Clausen AH: *Behaviour and Modelling of Dual-Phase Steels.* Presented at the 7th European LS-DYNA Conference, Salzburg, Austria, 13-15 May 2009.
10. Holmedal B: *Responses to strain-path changes.* Presented at Euromat 2009, Glasgow, Great Britain, 7-10 September 2009.
11. Wierzbicki T, Børvik T, Teng X.: *Experimental and numerical study on perforation with fragment formation.* Presented at IUTAM Symposium on Dynamic Fracture and Fragmentation, Austin, Texas, USA, 8-13 March 2009.

Poster presentations at conferences

1. Chen Y, Hopperstad OS, Clausen AH, Børvik T, Berstad T: *Finite element analyses of Charpy tests on extruded aluminium alloys.* Presented at 9th International Conference on the Mechanical and Physical behaviour of Materials under Dynamic Loading (DYMAT 2009), Brussels, Belgium, 7-11 September 2009.
2. Delhaye V, Polanco-Loria M, Berstad T, Clausen AH, Hopperstad OS, Moussy F, Othman R: *Characterization and numerical modelling of a polypropylene material applied in the automotive industry.* Presented at 14th International Conference on Deformation, Yield and Fracture of Polymers (DYFP 2009), Kerkrade, Netherlands, 5-9 April 2009.
3. Fyllingen Ø, Hopperstad OS, Langseth M: *Robustness study of top-hat sections of high strength steel subjected to axial crushing.* Presented at 3rd International Conference on Integrity, Reliability & Failure (IRF 2009), Porto, Portugal, 20-24 July 2009.
4. Moura RT, Clausen AH, Langseth M, Alves M: *Dynamic mechanical behaviour of polyethylene.* Presented at the 9th International Conference on the Mechanical and Physical behaviour of Materials under Dynamic Loading, Brussels, Belgium 7-11 September 2009. DYMAT2009.
5. Polanco-Loria M, Clausen AH, Berstad T, Hopperstad OS: *A constitutive model for thermoplastics in structural applications.* Proceedings at 14th International Conference on Deformation, Yield and Fracture of Polymers, pp. 261-264. Rolduc Abbey, Kerkrade, the Netherlands, 5-9 April 2009.
6. Reyes A, Hopperstad OS, Berstad T, Lademo O-G: *Forming limit diagrams with an FE-based approach for sheets under non-proportional loading.* Presented at the 7th European LS-DYNA Conference, Salzburg, Austria, 13-15 May 2009.
7. Snilsberg KE, Westermann I, Holmedal B, Hopperstad OS, Langsrud Y, Marthinsen K: *Anisotropy of Bending Properties in Industrial Heat-treatable Extruded Aluminium Alloys.* Presentd at the International Conference on Processing & Manufacturing of advanced materials, Berlin, Germany, 25-29 August 2009.
8. Tarigopula V, Albertini C, Langseth M, Hopperstad OS, Clausen AH: *A hydro-pneumatic machine for intermediate strain-rates: Set-up, tests and numerical simulations.* Presented at the 9th International Conference on the Mechanical and Physical behaviour of Materials under Dynamic Loading, Brussels, Belgium 7-11 September 2009.
9. Tarigopula V, Hopperstad OS, Clausen AH, Langseth M.: *Effect of pre-straining on localisation and fracture of dual-phase steel at elevated rates of strain.* Presented at the 9th International Conference on the Mechanical and Physical behaviour of Materials under Dynamic Loading, Brussels, Belgium, 7-11 September.
10. Westermann I, Hopperstad OS, Marthinsen K, Holmedal B: *Work- and Age-Hardening Behaviour of a Commercial AA7108 Aluminium Alloy.* Presented at the 4th International Light Metals Technology Conference, Gold Coast, Australia, 29 June – 1 July 2009.

www.ntnu.no/simlab

Annual Report for SIMLab Centre for Research-based Innovation 2009

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