# SIMLab
## Centre for Research-based Innovation
Annual Report 2014

**MAIN ACHIEVEMENT**

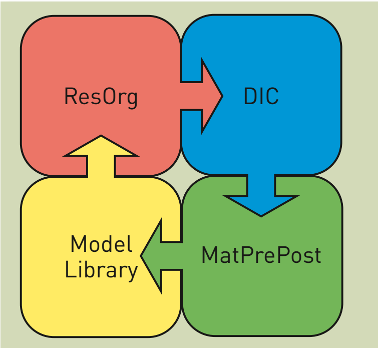
The SFI CASA application was approved

sfi Centre for Research-based Innovation

SINTEF

NTNU – Trondheim
Norwegian University of Science and Technology

# Contents






Industrial partners in 2014

HYDRO
Statoil
Forsvarsbygg
Audi
RENAULT
SSAB
Statens vegvesen
BMW
TOYOTA
BENTELER Automotive

# Summary

SIMLab (Structural Impact Laboratory) – Centre for Research-based Innovation – is hosted by the Department of Structural Engineering, Norwegian University of Science and Technology (NTNU) in cooperation with the Department of Materials Science and Engineering, 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 following 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. Examples of applications are safety innovations in the automotive and offshore industries, improved highway safety as well as protective structures for international peacekeeping operations.

The industrial partners in the Centre in 2014 were: Hydro, Audi AG, Renault, Toyota Motor Europe, BMW Group, Benteler Aluminium Systems, Statoil, SSAB, the Norwegian Public Roads Administration and the Norwegian Defence Estates Agency.

The overall management structure of the Centre consists of a board comprising members from the consortium participants. A 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 provides scientific and strategic advice based on a defined mandate.

The defined research areas for 2014 were linked with research programmes with focus on *Fracture and Crack Propagation (F&CP), Connectors and Joints (C&J), Polymers (Poly), Multiscale Modelling of Metallic Materials ($M^4$) and Optimal Energy Absorption and Protection (OptiPro)*. For each research programme, annual work plans were defined with contributions from PhD candidates, post docs and scientists

*The research group and industrial partners at the SIMLab conference in November 2014.*

Photo: Ole Morten Melgård

from the partners. The Demonstrator activity served as a link between the basic research and the industrial need for the technology developed and was gathered in a SIMLab Tool Box for implementation at the industrial partners.

Workshops and seminars were organized in order to strengthen the idea generation in the Centre and ensure transfer of technology from the Centre to the user partners.

The annual SIMLab conference and the board meeting were hosted by SIMLab in Trondheim, on 24-26 November 2014.

In 2014, research work in the Centre resulted in 18 papers published in peer-reviewed journals. In addition, 14 journal papers have been accepted, but not yet published. The research group has given 33 conference and seminar contributions and among them 6 keynote and invited lectures. The research in the Centre is carried out through close cooperation between master's, PhD candidates, post docs and scientists. In 2014, 24 male and 4 female master's students, 13 male and 1 female PhD candidates have been connected to the Centre. Further, 1 female and 2 male post docs are employed at SIMLab. Three international students, from Germany, Spain and the UK respectively, had research visits at the Centre during 2014. PhD candidates Marion Fourmeau, Henning Fransplass, Martin Kristoffersen and Dmitry Vysochinskiy have defended their respective theses on

*Characterization and modelling of the anisotropic behaviour of high-strength aluminium alloy,*

*Behaviour of threaded steel fasteners at elevated deformation rates,*

*Impact against X65 Offshore Pipelines, and Formability of aluminium alloy subjected to prestrain by rolling.*

*Formability of aluminium alloy subjected to prestrain by rolling.*

SIMLab's new test facility, the Shock tube, was officially opened on 20 October 2014. In conjunction with the opening a seminar was held with representatives from relevant public authorities in the field of physical security, i.e. the Norwegian National Security Authority, the Norwegian Defence Estates Agency, the Ministry of Local Government and Modernization, Ministry of Justice and Public Security, and the Norwegian Police Security Service. In addition the seminar was attended by representatives from the Research Council of Norway and the Norwegian state's building commissioner Statsbygg.

International cooperation and visibility are success parameters for a Centre. Thus the Centre has had cooperation (attended through common publications, Cotutelle agreements for PhD candidates and visiting scientists) with the following universities/research laboratories in 2014: Ecole Normale Supérieure de Cachan/Laboratoire de Mécanique et Technologie (ENS/LMT), France; University of Savoie, France; University of São Paulo, Brazil; European Commission, Joint Research Centre, Institute for the Protection and Security of the Citizen, Ispra, Italy; Karlsruhe Institute of Technology, Germany; Impetus Afea Sweden; Texas Institute for Intelligent Materials and Structures (Assoc. Professor Amine Benzerg).

With respect to visibility the activities in the Centre have been presented in Norwegian newspapers and magazines as well as on Norwegian television and radio. The cooperation between SFI SIMLab and SFI SAMCoT was shown on Discovery Channel as a part of the programme Daily Planet. Several concurrent research projects have been run in parallel with the Centre's activities. Furthermore, the Centre is involved in a EUROSTARS project on the development of a new non-linear simulation tool for mechanical and multi-physics problems using graphics processing units (GPU).

Finally, a new SFI Centre (Centre for Advanced Structural Analysis - CASA) was proposed on multi-scale testing, modelling and simulation of materials and structures for industrial applications. The leading group behind the application is SIMLab at the Department of Structural Engineering, NTNU. Cooperating units are the Department of Physics and the Department of Materials Science and Engineering at NTNU, and SINTEF Materials and Chemistry. The application was approved and SIMLab was awarded a new SFI Centre for the period 2015-2022.

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 requirements for innovation and value creation in an international market, Norwegian industry has to adopt new and original knowledge in product development. Thus efficient modelling of the whole process chain, through process 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 structure

# 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 22 PhD candidates where at least four are female. **2)** To graduate at least 10 MSc students annually. **3)** To attract at least 5 non-Norwegian professors/scientists during the duration of the Centre. **4)** To publish at least 15 papers in international peer-reviewed journals annually in addition to conference contributions. **5)** To arrange one international conference between 2007 and 2014.

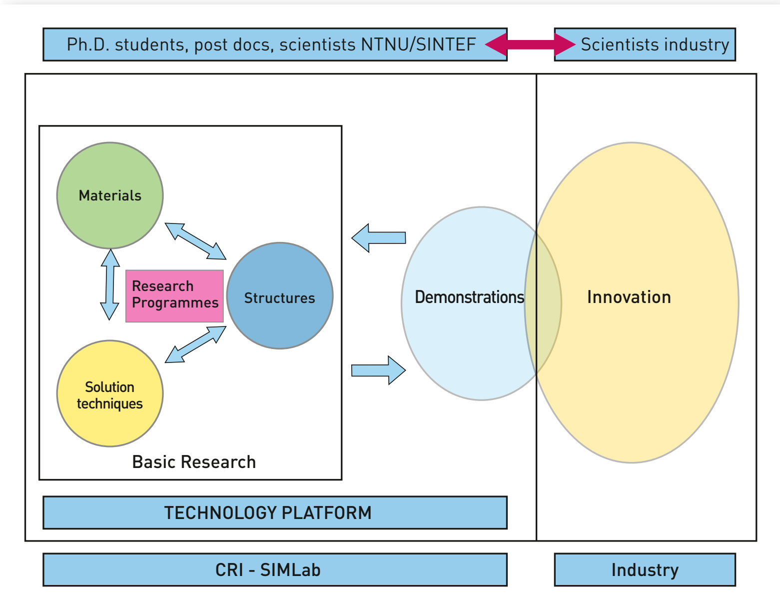
# Research areas

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.

The research area 'Structures' serves as a link between 'Materials', 'Solution techniques' and the "Demonstrators" activities, see the figure below. The selection of demonstrators/benchmark tests for validation is carried out in close cooperation with the industrial partners. Included in the "Demonstrators" activity is also the development of a SIMLab Tool Box where all the technology and models developed are gathered in order to facilitate the transfer of research carried out to 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 as well as the transfer of technology to the industrial partners.

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 following research programmes have been running in 2014:

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

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

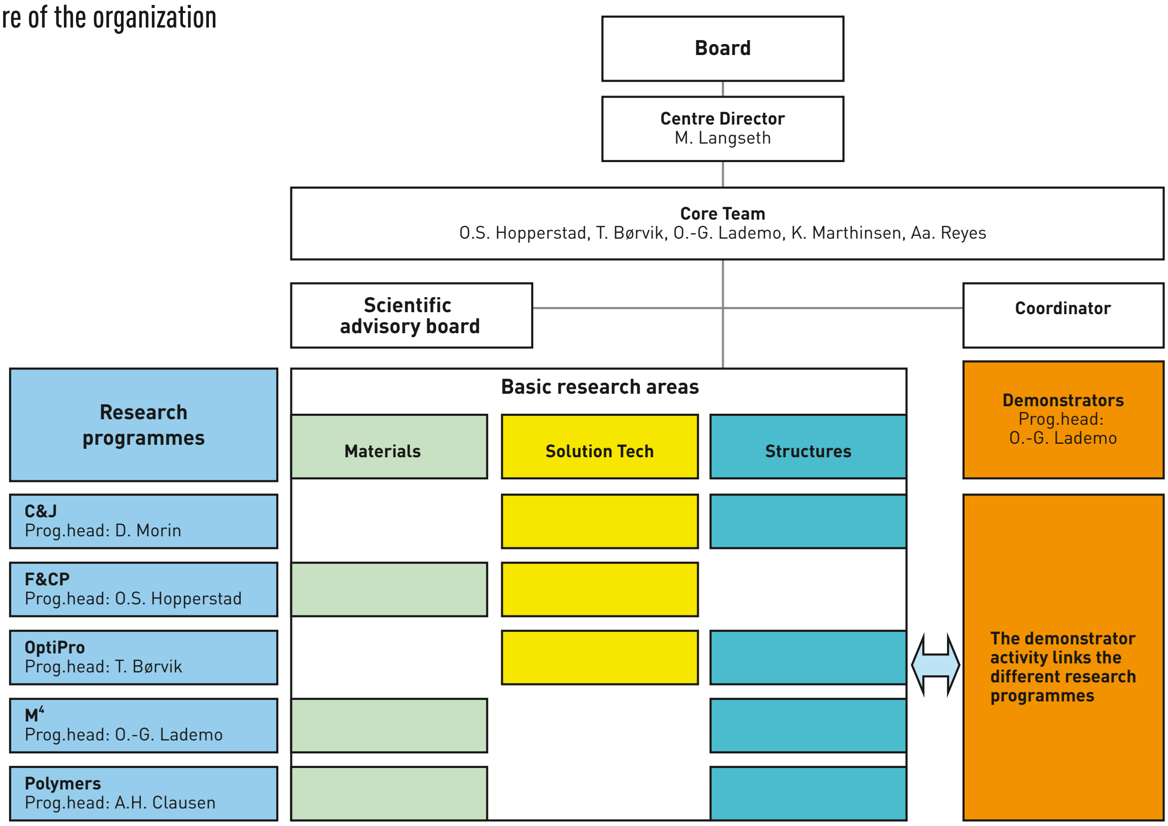
- ***Polymers (Poly):*** This will develop validated models for polymers subjected to quasi-static and impact loading conditions. An important prerequisite is to establish a set of test methods for material characterization and generate a database for validation tests. The programme for the time is limited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

- ***Multi-scale Modelling of Metallic Materials ($M^4$):*** 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 rivets, flow drilling screws and bolted connections subjected to static and dynamic loading conditions will be obtained. Special focus is placed on the establishment of a model to be used for large-scale shell analyses.

# Research organization

## Structure of the organization




*Structure of the organization in 2014.*

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. In 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/Head of Department, Department of Structural Engineering, NTNU (Chairman)
- Thomas Hambrecht, Head of Functional Design Body, Audi AG
- Rudie Spooren, Vice President Research, SINTEF Materials and Chemistry
- Håvar Ilstad, Manager Pipeline Technology, Statoil
- Hans Erik Vatne, Senior Vice President, Head of Technology, Hydro
- Helge Langberg, Head of the National Centre for Protection of Buildings, Norwegian Defence Estates Agency
- Per Kr. Larsen, Professor Em., Department of Structural Engineering, NTNU
- Joachim Larsson, Head of Product Development, SSAB
- Tsukatada Matsumoto, Project Manager, Toyota Motor Europe
- Sigurd Olav Olsen, Director of Civil Protection, Norwegian Public Roads Administration
- Thorsten Rolf, Team Leader – Simulation Methods, Body in White, BMW Group
- Anders Artelius, Head of Aluminium Technology, Benteler Aluminium Systems
- Eric Vaillant, Head of Department for Analysis, Behaviour and Environment Materials, Renault
- Astrid Vigtil, Head of Research Section, Faculty of Engineering Science and Technology, NTNU

## Centre Director

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

**Core Team and programme heads**
*From left: David Morin, Aase Reyes, Odd-Geir Lademo, Magnus Langseth, Tore Børvik, Peter Karlsaune, Knut Marthinsen, Odd Sture Hopperstad and Arild Holm Clausen.*

Photo: Ole Morten Melgård

Photo: Benedikte Skarvik

**Scientific Advisory Board** *From left: Klaus Thoma, Larsgunnar Nilsson, Norman Jones, David Embury, Ahmed Benallal and John Hutchinson.*

## Scientific Advisory Board

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

## Core Team and programme heads

- Tore Børvik, Professor, Department of Structural Engineering, NTNU
- Arild Holm Clausen, Professor, Department of Structural Engineering, NTNU
- Knut Marthinsen, Professor, Department of Materials Science and Engineering, NTNU
- David Morin, PhD and post doc at SIMLab
- Odd Sture Hopperstad, Professor, Department of Structural Engineering, NTNU
- Odd-Geir Lademo*, Dr. ing., SINTEF Materials and Chemistry
- Aase Reyes, Professor, Department of Structural Engineering, NTNU
- Peter Karlsaune, SIMLab coordinator

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

## Partners

- Host institution
  - NTNU

- Research partner
  - SINTEF Materials and Chemistry

- Industrial partners
  - Audi AG
  - Benteler Aluminium Systems
  - BMW Group
  - Hydro
  - Renault
  - SSAB
  - Statoil
  - Toyota Motor Europe
  - The Norwegian Public Roads Administration (NPRA)
  - The Norwegian Defence Estates Agency (NDEA)

## Core competence of the research team

The core competence of the research team is related to material modelling of metallic materials and polymers, material and component testing at various loading rates and development and implementation of material models suited for large-scale structural analyses. This competence serves as a basis for the research activities on materials and structures, taking into account the interaction between material behaviour, structural geometry and the manufacturing process. To support these modelling activities, the Centre has developed extensive experimental facilities for the testing of materials at elevated rates of strain and impact and crashworthiness testing of components and structural subsystems.

*Polymer seminar in Trondheim on 24 November 2014.*

### Cooperation within the Centre and interaction with the industrial partners

The annual work plans for each programme were defined with contributions from each partner. Scientists from NTNU and SINTEF and PhD candidates and post docs have been the main contributors to perform the work, while each industrial and public partner has participated based on their defined contribution in kind. The contribution in kind for Audi is mainly based on a PhD candidate working both at the Centre and at Audi. Furthermore, Hydro and Benteler Aluminium Systems are supporting professorial positions at SIMLab ensuring an excellent link between our master's students and the industrial partners as well as with the PhD candidates. The cooperation and spread of information in the main research group (NTNU and SINTEF) and between the industrial partners and the research group has been based on using programme and project meetings as well as seminars.

Once a week, the Centre Director has had a meeting with the programme heads and the core team members. These meetings are used to coordinate the activities in the research programmes and to ensure that the progress and cost plans as well as the deliverables are in accordance with the defined annual work plans. In addition, specific project meetings and seminars were held in each research programme when necessary with participation from all involved partners.

The project meetings, seminars and workshops were also supported by telephone meetings with our partners 1-3 times a year. In order to strengthen the spread of information in the Centre, a seminar was held each second week including a short presentation of a research topic by one of the Centre members (professors, scientists, PhD candidates and post docs).

### The Centre's Annual Conference and Board Meeting in Trondheim

The Centre's Annual Conference was held at Clarion Hotel & Congress in Trondheim on 25 November 2014. The conference programme had focus on what was achieved from a scientific point of view during the 8-year programme, how the research had been implemented and used by the industrial partners as well as a presentation on how visible the Centre has been to promote its research in media. Two of the Scientific Board members (Professor John Hutchinson and Professor Em. David Embury) gave a presentation on how the research at the Centre has evolved since 2007 with focus on scientific quality and relevance to the industrial partners. Finally, Professor Torger Reve from BI Norwegian Business School gave a talk on the need for research-based innovation in Norway.

The annual Board Meeting was held on 26 November at SIMLab.

# New SFI Centre

The SIMLab research group was awarded a SFI Centre named CASA (Centre for Advanced Structural Analysis) on 21 November 2014. The new Centre will deal with research on multi-scale testing, modelling and simulation of materials and structures for industrial applications. The research in this centre will be multidisciplinary and interdisciplinary in order to create a platform for credible numerical simulations of products and structures for innovation and value creation in the transportation industry, the oil and gas industry, and industry and public enterprises working with physical security.

The research will focus on structures made of steel, aluminium alloys, and polymers, hybrid structures as well as protective structures. The core group of professors and scientists behind the application is Tore Børvik, Arild Holm Clausen, Odd Sture Hopperstad, Odd-Geir Lademo, Magnus Langseth and Aase Gavina Reyes from the Department of Structural Engineering, Randi Holmestad from the Department of Physics and Knut Marthinsen from the Department of Materials Science and Engineering. Professor Odd-Geir Lademo is working at SINTEF and has at the same time an adjunct professorship, i.e. a 20% position at NTNU.

The user partners in the Centre, each representing one or more of the defined business sectors, are Aker Solutions, Audi, Benteler Aluminium Systems, BMW Group, DNV-GL, Gassco, Honda R&D Americas, Hydro, Ministry of Local Government and Modernisation, Norwegian National Security Authority (NSM), Norwegian Defence Estates Agency (NDEA), Norwegian Public Roads Administration (NPRA), Sapa, SSAB, Statoil and Toyota Motor Europe.

# Wind-up

The SFI SIMLab Centre was closed from 31 December 2014, i.e. the industrial consortium was dissolved from the same date. However, 10 PhD projects will continue upon the theses are defended in 2015 (5 students), 2016 (2 students) and 2017 (3 students).

# Research programmes and demonstrators

Research in the Centre is based on annual work plans. Thus each research programme and demonstrator activity is composed of several research projects. The following highlights some of the activities carried out.

## Fracture and Crack Propagation (F&CP)

**Head of Programme: Odd Sture Hopperstad**

The main objective of the F&CP programme has been to develop mathematical models and numerical algorithms for damage, fracture and crack propagation in ductile and semi-brittle materials, to establish robust calibration procedures, and to validate the models against laboratory tests using novel measurement systems. Rolled, extruded and cast aluminium alloys and high-strength steels have been studied in the programme. Novel fracture models have been developed and validated for dual-phase steel and cast aluminium alloys in the PhD theses of Gaute Gruben and Octavian Knoll, respectively, while Marion Fourmeau studied the plastic behaviour and ductile fracture of a strongly anisotropic, high-strength rolled aluminium alloy in her PhD thesis. During his work as PhD candidate and postdoctoral fellow at SIMLab, Egil Fagerholt has developed novel digital image correlation software with special features for analysis of crack propagation.

The research activities in 2014 have had main emphasis on the physical mechanisms and numerical models for fracture in aluminium alloys—but also work-hardening has been studied, as a proper description of work-hardening is essential in modelling of ductile fracture. A large experimental study has been completed and reported in several journal publications. The study provides valuable and new information on the influence of microstructure (i.e., solutes, particles and crystallographic texture) on work-hardening and ductile fracture of aluminium alloys. Aluminium alloys were purpose made by Hydro and subjected to three successive processing steps: 1) DC casting and homogenization, 2) hot extrusion, and 3) cold rolling and recrystallization, prior to tensile testing using smooth and notched samples. The microstructure of the alloys was characterized by optical and scanning electron microscopy, and fractography was used to investigate the fracture modes. An experimental-numerical method for determining the work-hardening curve to failure, using a laser-based measurement system, finite element analysis and optimization techniques, has been developed. If the alloys have crystallographic texture, polycrystal plasticity calculations are adopted to find the yield surface based on texture data prior to the optimization procedure.

The results confirm the observation made in previous studies that the tensile fracture strain scales with the yield strength for a constant microstructure; i.e., the failure strain decreases linearly with increasing yield strength. The Gurson model has been used to describe the stress-strain behaviour of the materials with random texture, and found to accurately describe the material softening due to void growth. The plastic anisotropy, induced by the extrusion process and not entirely removed by cold rolling and recrystallization, led to a wide range of fracture modes of the tensile samples, see Figure 1. Crystal plasticity finite element simulations were used to confirm that the rhombic shape of the fracture surface for the extruded material was due to strong cube texture and the geometric constraint by the pre-machined notch. The development of an anisotropic porous plasticity model for aluminium alloys is part of the PhD study of Lars Edvard Bryhni Dæhli on

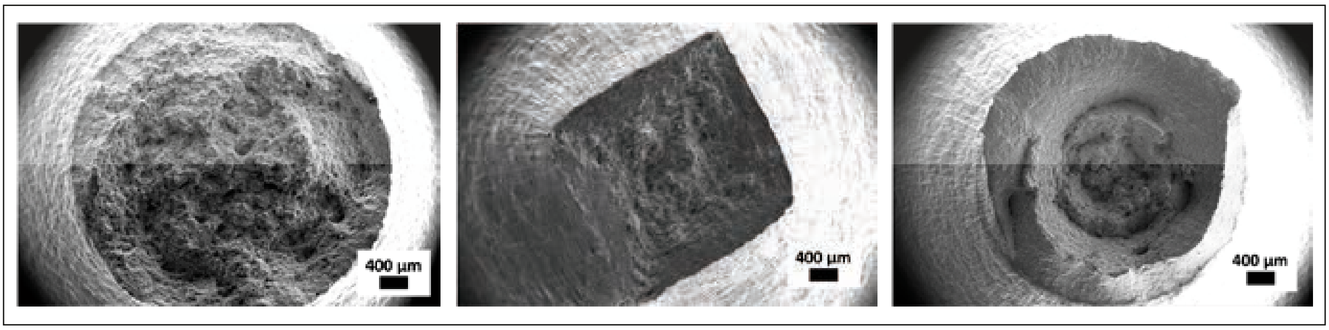



*Figure 1 Fracture surfaces from tests on notched samples made of cast and homogenized, extruded, and rolled and recrystallized materials (from left to right).*

micromechanical modelling of ductile fracture in aluminium alloys. The established experimental database, polycrystal plasticity calculations and finite element based void/particle containing unit cells with plastic anisotropic matrix material will be used to study the damage evolution and ductile fracture of textured aluminium alloys and to develop porous plasticity models for these materials.

## Optimal Energy Absorption and Protection (OptiPro)

**Head of Programme: Tore Børvik**

The main objective of the OptiPro programme has been to develop knowledge and tools for safer and more cost-effective design of protective structures. To meet these challenges, product development is increasingly carried out in virtual environments by the use of numerical methods in order to improve the protection. The new designs also need to be checked, improved and validated through high-precision experimental tests. The research activities in 2014 in the OptiPro programme have mainly focused on the following fields: 1) Impact against pipelines, 2) Blast loading on structures, 3) Protective structures and 4) Penetration in granular materials.

A PhD project has been defined within the three first research areas. The PhD project by Martin Kristoffersen on impact against pipelines finished in December 2014, while the PhD project by Vegard Aune on blast loading on structures and the PhD project by Jens Kristian Holmen on protective structures will finish in 2016. Another main activity in 2014 has been to establish a new shock tube facility at SIMLab as a part of Aune's PhD project. The shock tube was delivered and mounted in September/October, and was officially opened on the 20 October 2014. All these research activities have been run in close collaboration with a number of master's students.

The last main activity in 2014 dealt with penetration of granular materials by small-arms bullets. In the experimental tests, five different types of granular material (0-2 mm wet sand, 0-2 mm dry sand, 2-8 mm gravel, 8-16 mm crushed stone and 16-22 mm crushed rock) were impacted by four different types of small-arms bullets (7.62 mm Ball with a soft lead core, 7.62 mm AP with a hard steel core, 12.7 mm Ball with a soft steel core and 12.7 mm AP with a tungsten carbide core). The tests were carried out using different rifles to fire the projectiles, while the granular materials were randomly packed in a 320 mm diameter specially-designed steel tube. In all tests, the initial projectile velocity and the depth of penetration in the granular material were measured for each bullet type. In the numerical simulations, a discrete particle-based approach was used to model the behaviour of sand during bullet impact. The method works with discrete particles that transfer forces between each other through contact and elastic collisions, allowing for a simple and robust treatment of the interaction between the sand particles and the bullet which is represented by finite elements. An important observation from this study is that the penetration depth is strongly influenced by deviation of the bullet from its original trajectory. Good agreement between the available experimental results and the numerical predictions is also in general obtained. The modelling principle is illustrated in Figure 2.

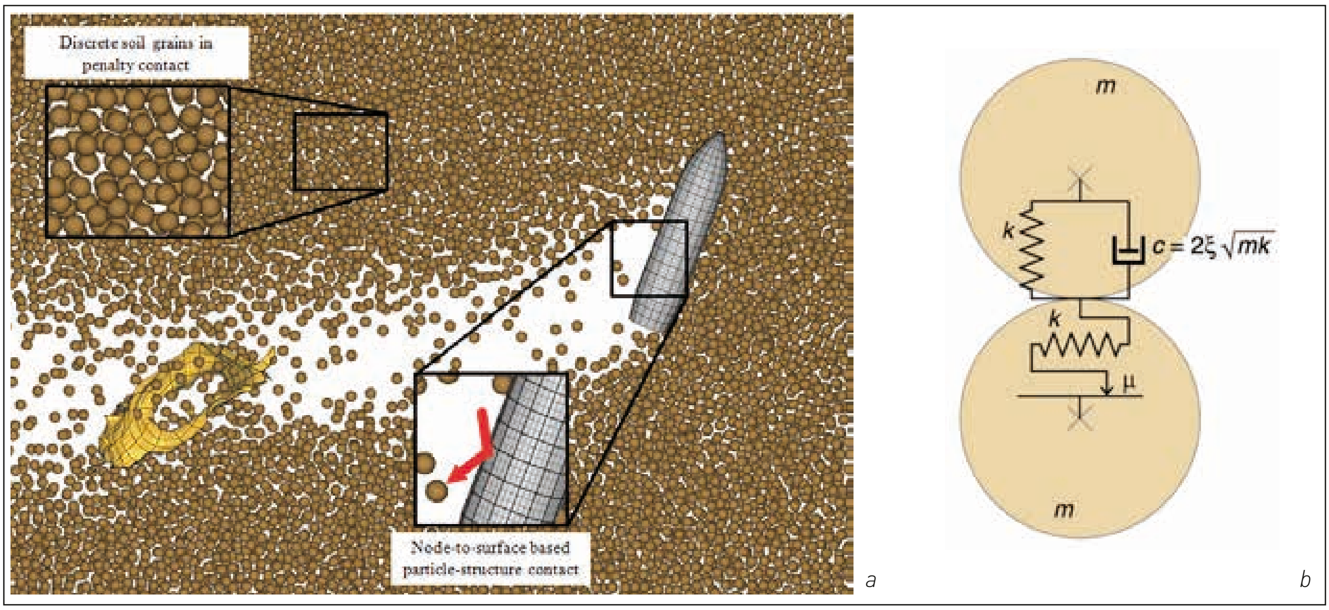



*Figure 2 a) Modelling principle of the discrete particle-based method for the interaction between a penetrating AP bullet and the sand grains, and b) rheological model for the sand interaction.*

## Polymers

### Head of Programme: Arild Holm Clausen

The objective of the Polymers programme has been to develop validated material models for polymers. Most of the research has been related to ductile thermoplastics, but an activity on fibre-reinforced polymers was launched in 2013. The main attention has been paid to constitutive models representing the stress as function of strain and strain rate, but also simple fracture models have been implemented. An important delivery to the industry partners has been the incorporation of some generic models for polymers in the SIMLab Tool Box.

The research activities in 2014 have been within the following fields:

- Implementation, verification and validation of models in the SIMLab Tool Box.
- Large-strain response of ductile thermoplastics.
- Characterization of glass-fibre reinforced polymers.

The first of these projects has gained major attention since 2012. The polymer part of the Tool Box now includes a hypoviscoelastic–viscoplastic model. Depending on the material and problem at hand, the viscoelastic and viscoplastic parts may be switched on or off. Anisotropic elasticity, which is relevant for fibre-reinforced polymers, is also implemented in the model. Further, three damage models are included. For validation, there has been cooperation with Toyota, in particular through the master thesis of Heine Røstum, which was carried out at Toyota Motor Europe's Technical Centre in Brussels from September 2013 to February 2014. Such a joint master thesis served to enhance the application of the Tool Box at Toyota, and seems to be an adequate way of implementing technology at the user partners.

One of the topics of Marius Andersen's PhD project has been to obtain reliable experimental data at large plastic deformations. Accurate information on the true stress-strain response as well as possible change of volume is important for material modelling. As a part of his project, Andersen has developed a tension test sample that facilitates deformation to much larger strains than more conventional specimens do. The samples are shown in Figure 3. The improved sample has a circular cross-section, a comparatively short gauge length, and the shoulders are also kept short. As shown in Figure 4, the true stress-strain curve can be determined for strains exceeding 200% with the new specimen, and the true stress at fracture is more than 160 MPa. The strain components were determined with digital image correlation (DIC). It is observed from Figure 4 that the true stress of the conventional sample is smaller. The reason for this is that the corners introduce a constraint on the contraction, implying that the transverse strain is smaller than for the improved sample. Consequently, the area is comparatively larger, implying a reduced level of the true stress.

Andreas Koukal defended his PhD thesis on glass-fibre reinforced polymers in June 2014. Although the degree was awarded by Technische Universität München (TUM), he did a major part of his material test programme at SIMLab. Petter Henrik Holmstrøm started his PhD project

*Figure 3* *Improved tension test sample (circular cross-section) and conventional sample (rectangular cross-section).*

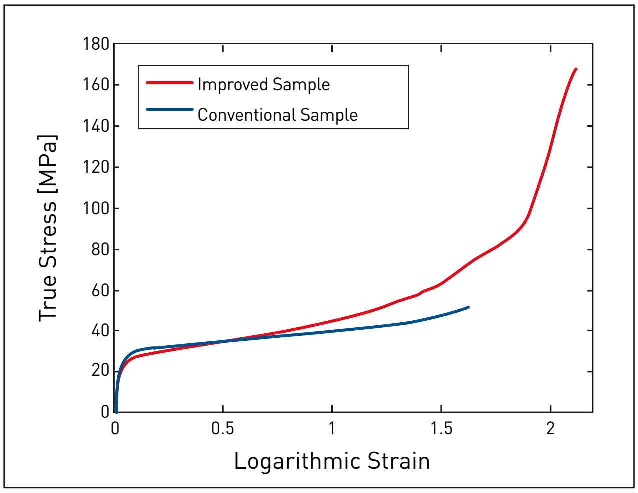



*Figure 4* *True stress-strain curves for a ductile high-density polyethylene (HDPE) obtained with improved and conventional tension test samples.*

on the modelling of fibre-reinforced materials in August 2013. Improved material models should in some way take the distribution of fibre orientation angles into account. A preliminary computer tomography (CT) scan of a polypropylene reinforced with glass fibres, see Figure 5, shows promising results.

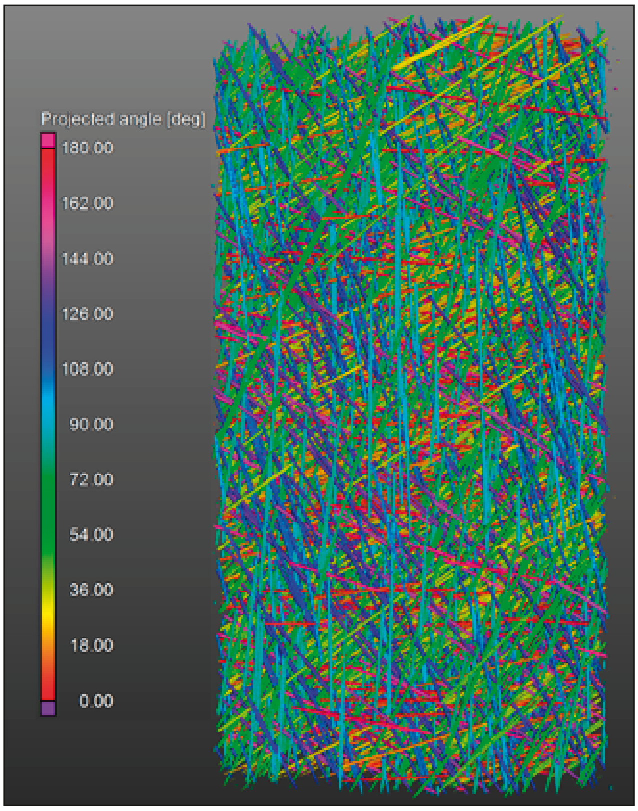



*Figure 5* *Computer tomography (CT) scan of a glass-fibre reinforced polypropylene (PP). Reconstruction performed by Nikon.*

## Multiscale Modelling of Metallic Materials ($M^4$)

**Head of Programme: Odd-Geir Lademo**

The main objective of the M4 programme is to develop a multiscale modelling framework that enables an integrated design of material, process and product in a virtual process line. At the macro level the modelling relies upon and contributes to the development of the phenomenological SIMLab Metal Model. At lower (meso-/crystalscale) level, a framework for single- and polycrystal plasticity has been developed (including the SIMLab Crystal Plasticity Model). At microscale, a precipitation-based modelling procedure (NaMo) is used and developed that describes strength and work hardening as function of the chemical composition of the alloy and the thermal history.

The research activities in 2014 have carried out work in the following four fields, each involving contributions and/or results from a PhD candidate:

- Fundamentals of multiscale modelling.
- Formability of sheet materials.
- Capacity and ductility of welded structures.
- Behaviour of aluminium at wide ranges of strain rate and temperature.

The first project is designed to provide qualitative insight and quantitative estimates on the effects of meso- and microscale properties on the macroscopic behaviour of the material. In 2014, further work has been done to finalize and document a number of scientific studies. The associated PhD candidate Mikhail Khadyko submitted his PhD thesis in October 2014.

In the second project, work is done to i) establish experimental procedures to study and characterize strain localization and failure in sheet materials and ii) to perform targeted development of the model framework to represent the observed phenomena. Figure 6 illustrates the tool developed to detect formability limits from experimental formability tests using standardized and research-based methods. PhD candidate Dmitry Vysochinskiy defended his thesis on 16 December 2014.

The third project is designed to refine the established "virtual process line" for integrated design of welded aluminium structures (alloys, welding and Post-Weld Heat Treatment (PWTH) process parameters, and product geometry). The concept makes use of the precipitation based modelling procedure (NaMo) to feed a precipitate-based strength and work hardening model formulated at the macroscale. In 2014, Hydro Aluminium has made further progress to close gaps identified in the PhD study of Anizahyathi Alisibramulisi. The modelling concept has further been implemented and used in various other research programmes in the Centre.

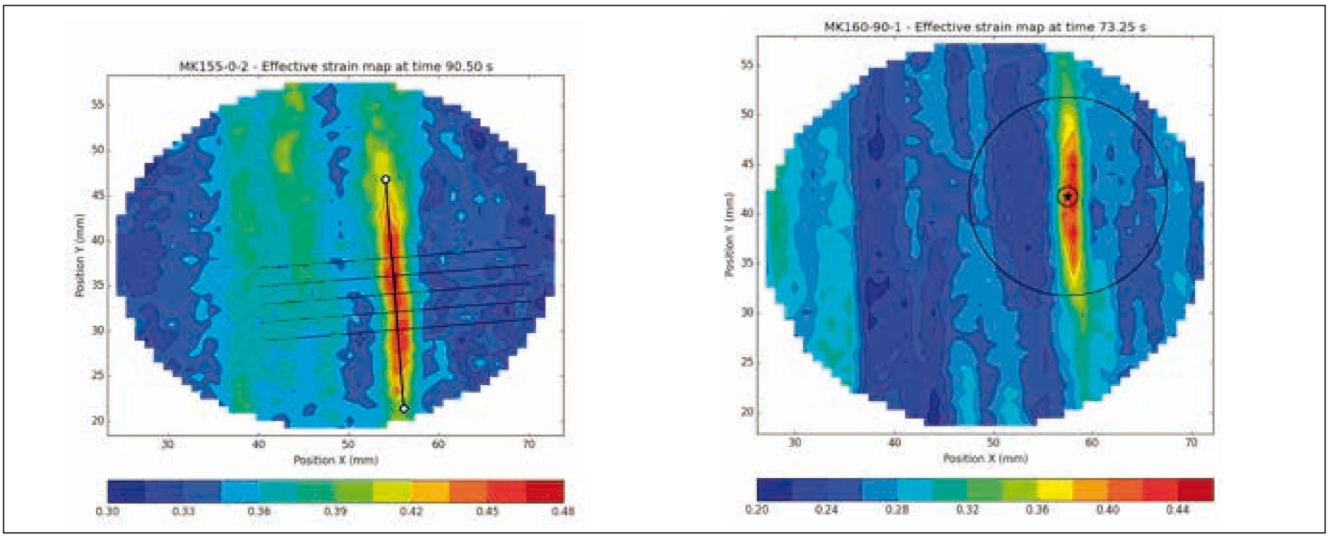



*Figure 6 Automated detection of formability limits by aid of purpose-made software program supporting a) the standardized intersection method and b) various research-based algorithms.*

The last project aims to i) establish methods for testing metallic materials at wide ranges of temperature and strain rate; ii) enhance the understanding of the underlying material mechanisms; and iii) evaluate and further develop the model framework for these conditions. The research work focuses on aluminium alloys, and was done by PhD student Vincent Vilamosa who submitted his thesis in December 2014.

## Connectors and Joints (C&J)

### Head of Programme: David Morin

Modelling of structural assemblies requires proper modelling of connections, such as rivets, welds, bolts and adhesives. The level of detail in the modelling is again dependent on the modelling scale of interest. For large-scale crash analyses, simplified and computationally efficient models have to be used. However, the models should represent the large deformation behaviour and connector failure with a fair degree of accuracy. For local studies (i.e. small scale analyses), a higher amount of details can be built into the models allowing the use of more accurate and less time-consuming approaches than are otherwise available.

In this research programme, behaviour and fracture of connections are handled from both an experimental and numerical points of view. The experimental activities involve both studies on the behaviour of single connectors as well as the assembly of connectors used in structural joints. These experiments are carried out at low and high strain rates to gain increased understanding of the phenomena occurring during the large deformation behaviour of connectors. The numerical activities are divided into two modelling scales, i.e. a macroscopic and a mesoscopic scale. The macroscopic modelling is suitable for large scale analyses, but requires testing of single connector specimens for the calibration of the proposed models. In addition, since macroscopic modelling is a highly simplified way of representing joints, the quality of the prediction can then be of a moderate accuracy. On the other hand, mesoscopic models are based on accurate description of the joints with solid elements. This approach relies only on material properties and process simulations but requires a high amount of computational time.

Over the past years, the above methodology has been applied to several joining techniques, i.e. self-piercing rivets, structural bonding and bolted connections. In 2014, three activities have been carried out:

- Behaviour and fracture of bolted connections for road-restraint systems (as a continuation of the PhD thesis of Henning Fransplass),
- Behaviour and fracture of flow-drilling screws (as a continuation of the activity started in 2013 on the same topic),
- Behaviour and fracture of bolted connections under transient loadings (PhD project of Erik Grimsmo).

The two first activities have been carried out by master's students involving two students in each activity. The PhD project of Erik Grimsmo is concerned with quasi-static and impact loading of bolted steel connections. The design codes for such structures are in general

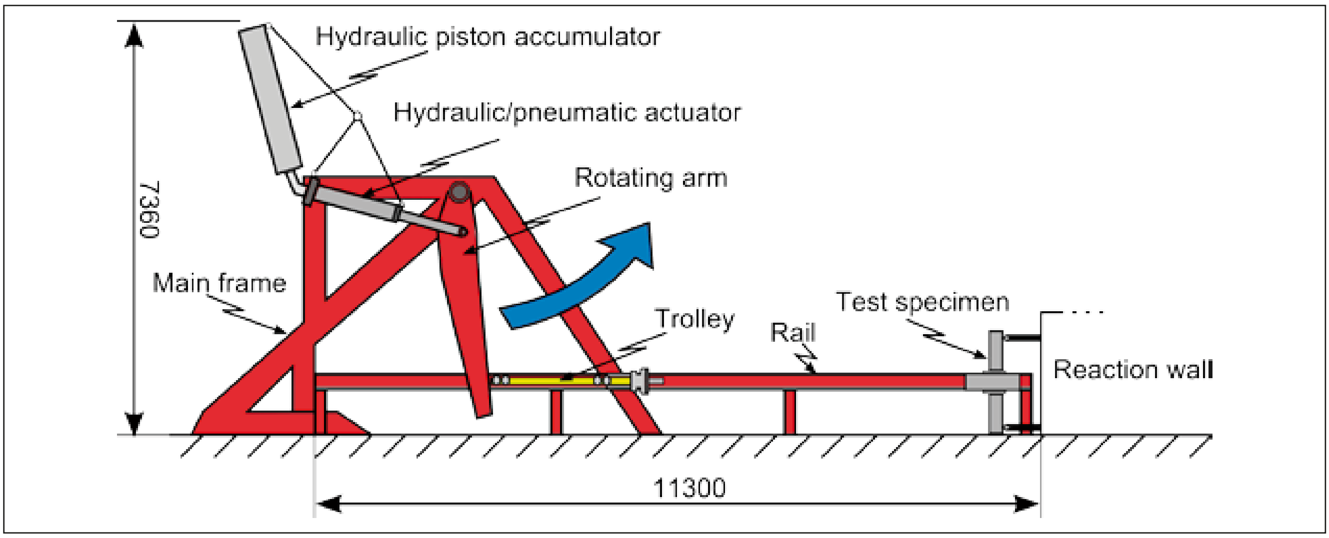



*Figure 7* *Experimental set-up for a dynamic test in SIMLab's pendulum accelerator.*

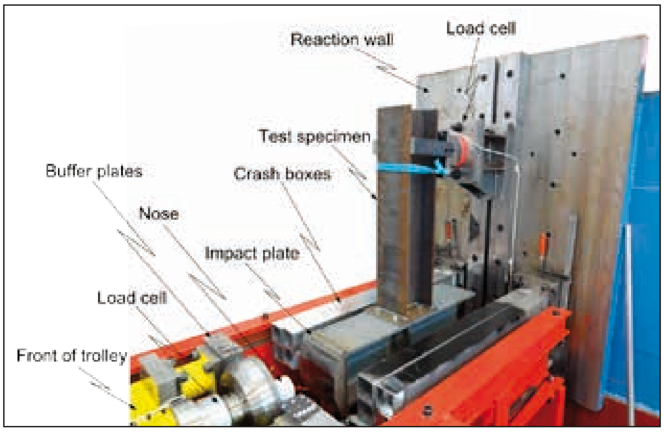



*Figure 8* *Close view of trolley and test specimen.*

developed for systems subjected to static loads or fatigue. To date, investigations on how joints in steel structures behave under dynamic loads caused by for instance sudden accidents or terrorist acts are scarce in the scientific literature. Figure 7 shows the set-up for a dynamic test carried out using the SIMLab's pendulum accelerator ("Kicking machine"). The specimens were mounted such that the trolley hit the column, which further loaded the connection with moments and shear forces, see Figure 8. The trolley had a mass of approx. 700 kg, and the impact velocity varied between 6 and 12 m/s. The results from the experimental tests serve to validate a numerical model of the joints.

## Industrial Demonstrators (Demo)

**Head of Programme: Odd-Geir Lademo**

The main objective of this research area is to facilitate industrial implementation of results produced in the Centre (e.g. experimental procedures and modelling concepts). In 2014 the work on the various software products and modelling guidelines has been given strengthened emphasis. The resulting 'SIMLab Tool Box' has been presented in detail in past annual reports. Below, only some results are highlighted.

### SIMLab Tool Box: Highlights 2013

The toolbox supports a number of applications relating to material characterization, parameter identification and numerical analysis and is, as such, applicable to help solve various challenges along an industrial value chain as illustrated in Figure 9.

Each software product may be used independently of each other or, to achieve maximum benefit, in proper combination(s). A new 'SIMLab Tool Box App' has been developed that provides a single access point to the tools and that further eases the management of projects and the related workflow, the associated data and rapid access to related documentation.

The 'Getting started' window in this new application is shown in Figure 10. The icons in the left column provide direct access to each of the tools and associated documentation and manuals.

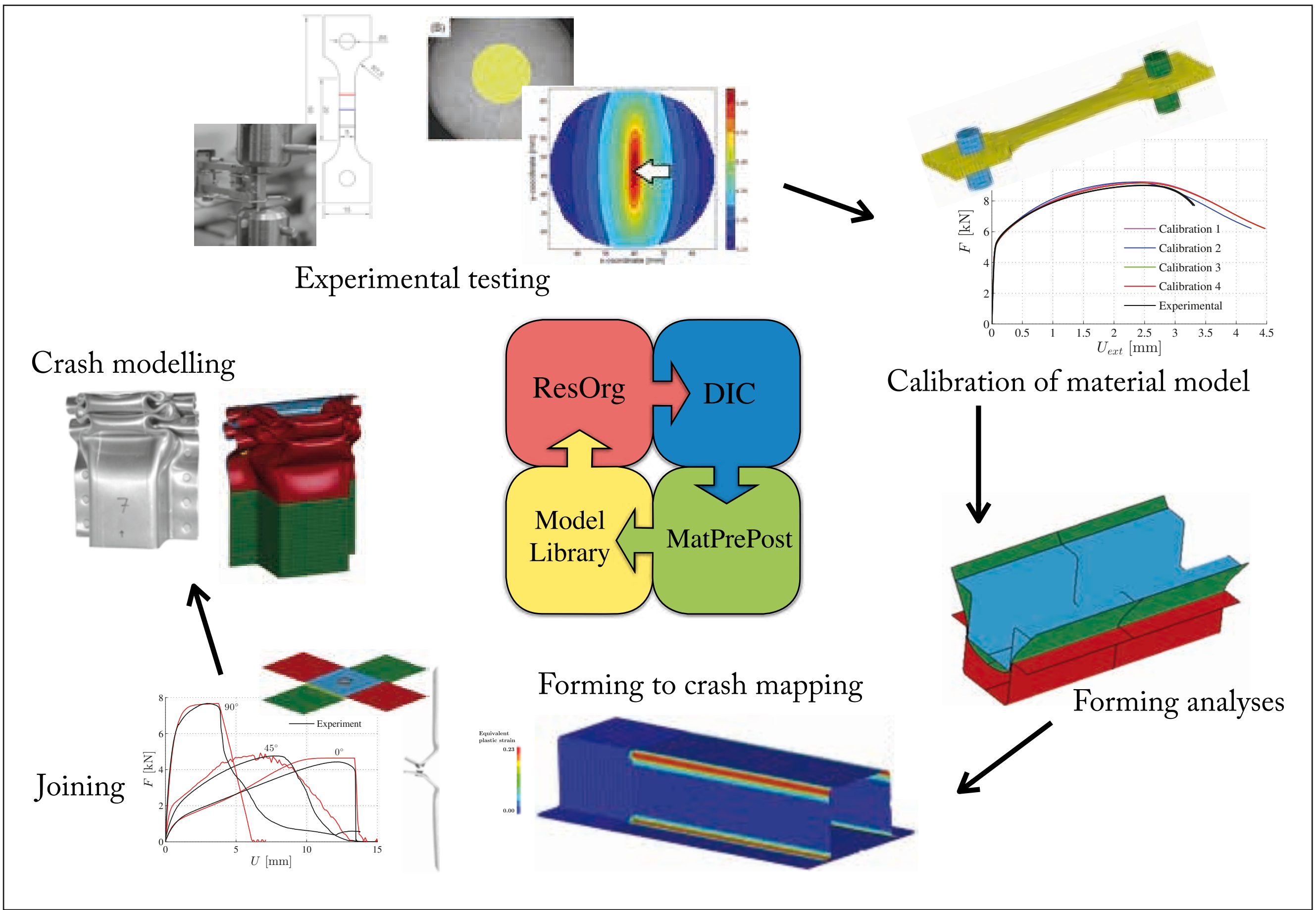



*Figure 9* 'SIMLab Tool Box'.

Each and every one of the various software components have been subject to further development during the year. The DIC software has been further extended and improved with respect to its functionality and ease-of-use.

The coupling of the DIC software with the model library has been a main task, even though this functionality is not ready for release. Through recent development of the Model Library, the SIMLab Metal Model may now be

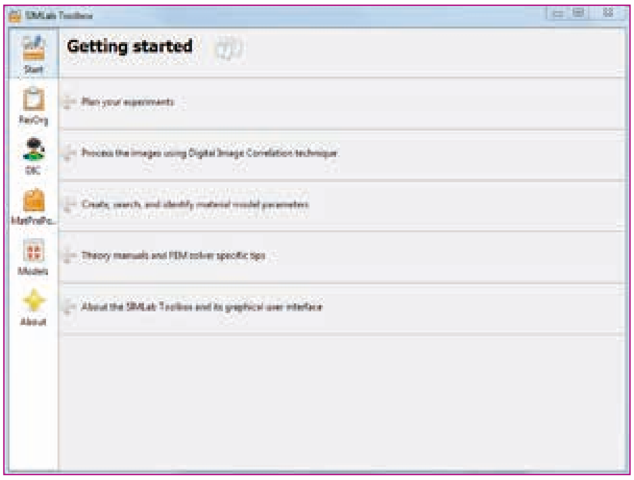



*Figure 10* 'Getting started' window in GUI for the 'SIMLab Tool Box App' – the all-in-one tool.

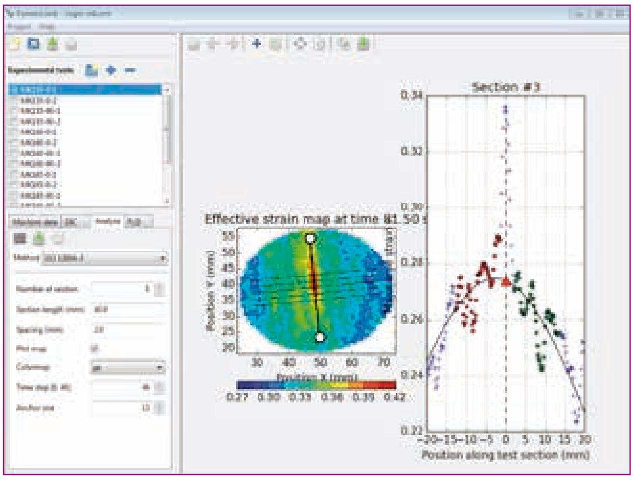



*Figure 11* Illustration of the new 'FormingLimitApp' for experimental detection (using DIC) and analytical prediction (using SIMLab Metal Model) of forming limits.

used with implicit solvers. This functionality is, however, not yet verified and validated for all FE solvers used by the industrial consortium. In MatPrePost issues and bugs reported by internal and external partners have continuously been addressed. Some features relating to formability prediction have been simplified, while work on a separate 'FormingLimitApp' has been instigated to support expert personnel with need of the most complex features in this application area. An example window from this new software tool is shown in Figure 11.

Several partners have run or are running dedicated projects to implement the SIMLab Tool Box and are supported by SIMLab personnel. To simplify a broad dissemination and practical use of the tools in these complex companies, a set of expandable tutorials and example studies are under development that will be linked up in the 'SIMLab Tool Box App'.

## Concurrent research projects

Utilizing the high level of expertise at the Centre, a selection of research projects that have been run in 2014 is presented. These include:

- *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 photovoltaics industry long-term access to world leading technological and scientific expertise.

- *Joint research project with Honda R&D Americas (2013-2017)*: The objective of the project is to model the behaviour and failure of flow drilling screws submitted to crash loadings. One PhD candidate works on the project supervised by personnel from the Centre.

- *Design and development of novel shock absorption systems to reduce injury during vehicle collisions (2015-2018)*: The aim of the project is to develop an efficient, light and cost effective generic frontal crash management system for passenger cars. Unlike most existing works where the focus is on the collapse of a single tube, the project will examine the energy absorption capacity of an integrated frontal crash box system that contains bumper bar, conical and prismatic deformable frustra attached to longitudinals. Apart from the integrated nature of the work to be carried out, the focus will be on the use of light alloys such as aluminium and magnesium as well as carbon fibre and glass fibre reinforced composites. The cooperation partners are SIMLab at NTNU, University of Toronto, Canada and Qatar University, Qatar. The application was approved in 2014 and the work is funded by Qatar National Research Fund.

- *Development of recommended practise for use of nonlinear FE-analysis to determine structural capacity (2014)*: SIMLab at NTNU is involved in a joint industry project together with DNV-GL Oil & Gas to develop recommended practice for use of nonlinear numerical analysis for steel structures in the oil and gas industry. The main work of SIMLab is to give guidelines with respect to constitutive modelling of steels including fracture prediction for large scale shell analysis.

- *Fundamental studies of materials' behaviour in future cold climate applications (SMACC) (2013-2018)*: NTNU and SINTEF are involved in this joint industry project. SINTEF is the project host. SIMLab is involved in the project with a PhD candidate working on behaviour and modelling of thermoplastics at low temperatures.

- *EUROSTARS GEPEU (2012-2015)*: This project works with the development of a new non-linear simulation tool for mechanical and multi-physics problems using graphics processing units (GPU) for computations. This is a new use of hardware technology for high computational speed. NTNU's role is to carry out validation of the proposed software. The partners in the project are Impetus Afea Norway (coordinator), Impetus Afea Sweden, NVIDIA Corporation, Centro Ricerche Fiat and NTNU.

# SIMLab test facilities

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

## Material testing at elevated rates of strain

### Split-Hopkinson Tension Bar (SHTB)

The split-Hopkinson tension bar, see Figure 12, is a device for material testing at strain rates in the range between 100 and 1500 $s^{-1}$. It consists of two steel bars with 10 mm diameter. They are denoted input and output bars, having lengths of 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 pre-stressed by means of a jack attached at the end of the bar. By releasing the lock, an elastic stress wave is released, propagating towards the sample with a velocity of 5100 m/s. Applying one-dimensional wave theory, the response of the specimen, i.e. stress, strain and strain rates, is determined from records of strain gauges glued to each bar. High-speed camera instrumentation is also feasible. Moreover, an induction heater also facilitates tests 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

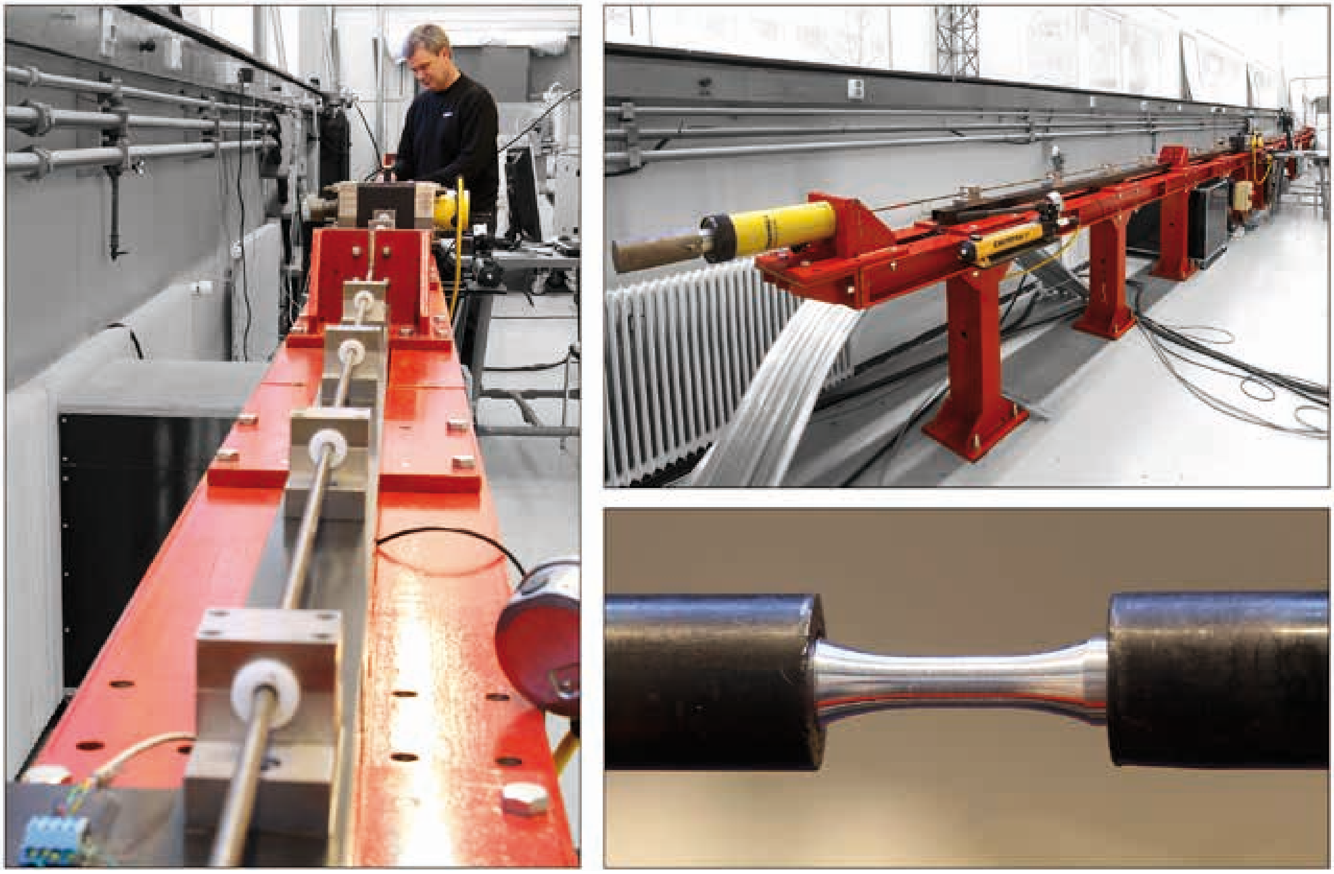


Photo: Melinda Gaal

*Figure 12* *Split-Hopkinson tension bar.*

aluminium. Two designs of the test samples are possible; axisymmetric with diameter 2-3 mm in the gauge part, or sheets 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.* International Journal of Impact Engineering 38 (2011) 824-836.

## Split-Hopkinson pressure bar (SHPB)

The new split-Hopkinson pressure bar at SIMLab, Figure 13, consists of a high-pressure chamber unit that can accelerate a projectile against the end of the input bar. The diameter of the projectile and thus the input and output bars, which are made of steel, are in the range 16-32 mm. The length of the projectile is 1750 mm, giving a maximum pulse length of 70 ms. The high-pressure chamber has the capacity to accelerate a projectile with a diameter of 32 mm up to an impact velocity of 20 m/s. The data acquisition of the new bar is the same as for the split-Hopkinson tension bar, i.e. the relative deformation of the compressed specimen as a function of time can be calculated from strain gauge measurements on the input and output bars and one-dimensional stress wave theory.

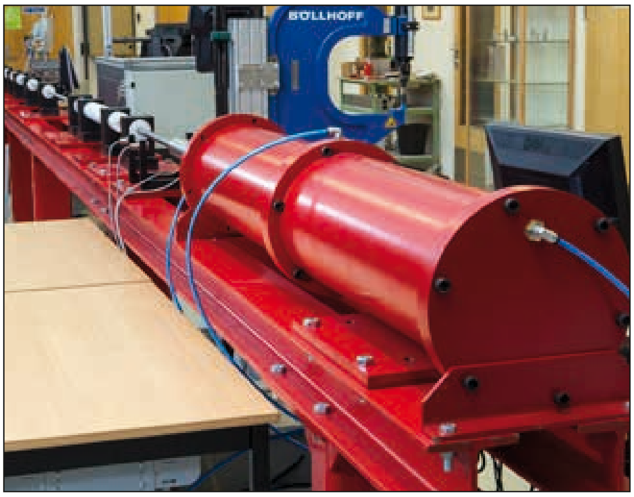



*Figure 13 Split-Hopkinson pressure bar.*

Photo: Ole Morten Melgård

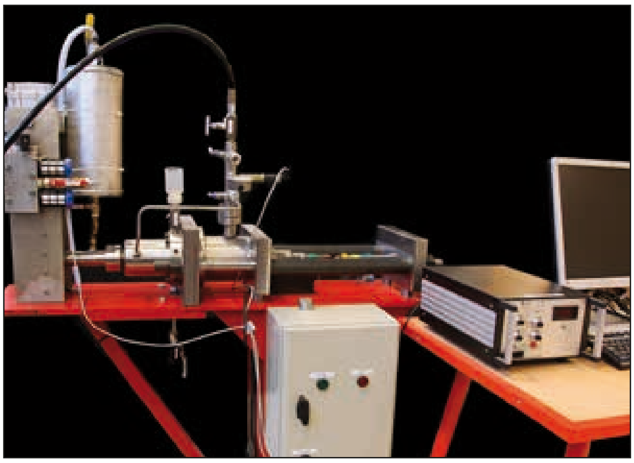


*Figure 14 Hydro-pneumatic machine.*

Photo: Melinda Gaal

## Hydro-pneumatic machine (HPM)

The hydro-pneumatic machine (HPM), see Figure 14, is a device for tensile material testing. It operates in the strain–rate range between 1-100 s-1. The specimen, which has the same dimensions as the sample applied in the split-Hopkinson tension bar, see Figure 12, is connected to two bars with diameters in the range 8-12 mm. The facility is mainly operated by gas and water with 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 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 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. The specimen elongation is measured by means of a displacement transducer sensing the displacement of a metallic strip connected to the piston shaft.

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 temperature.

***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 381-387.

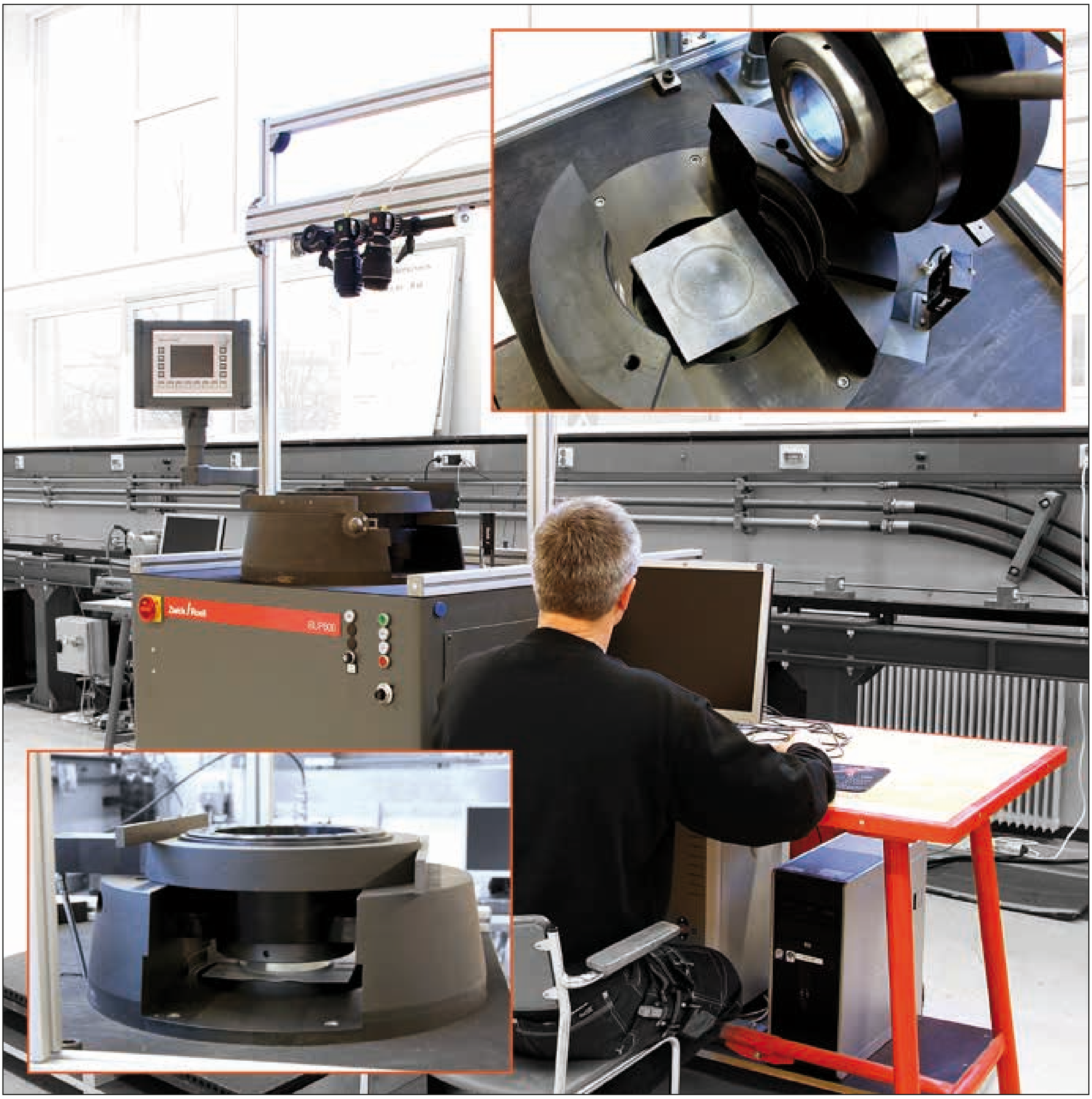



*Figure 15   BUP 600 machine.*

## Component and structural testing

### Sheet metal testing machine (BUP 600)

This fully PC-controlled multi-purpose hydraulic sheet metal forming machine, see Figure 15, is designed for testing the formability of sheet metals in accordance with the most common standards and procedures. Its main advantages are easy and rapid inter-changeability of the test tools, availability of tools for all well-known test standards and procedures, low cylinder-piston friction delivering accurate measurement acquisitions and excellent reproducibility, and numerous modular possibilities of extensions. These features make this machine an excellent means for performing advanced research to study forming processes and for the validation of numerical models. 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. It is compact with a volume a 1000x1485x1280 $mm^3$. 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.

The machine has been equipped with a pair of high resolution black and white Prosilica cameras GC2450, with a resolution of 2448×2050 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 K.O., Hopperstad O.S.: *Identification and validation of constitutive model and fracture criterion for AlMgSi alloy with application to sheet forming,* Materials & Design 2009; 30: 3005-3019.
Gruben G., Vysochinskiy D., Coudert T., Reyes A., Lademo O.-G.: *Determination of Ductile FractureParameters of a Dual-Phase Steel by Optical Measurements*. Strain 49:3 (2013) 221-232.

## Pendulum accelerator (Kicking machine)

The pendulum accelerator is a device for impact testing of components and structures, Figure 16. The test rig accelerates a trolley on rails towards a test specimen fixed to a reaction wall. The reaction wall has a total weight of 150 000 tonnes and is floating on the laboratory floor by using special-purpose designed shock absorbers. 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 800 -1500 kg, giving a maximum velocity between 35 m/s and 26 m/s. The velocity is measured by a photocell system. In case the specimen does not have sufficient energy absorption capabilities to stop the trolley, a secondary energy absorbing system is installed.

During testing, the trolley and the reaction wall can be equipped with load cells where each of the axial forces as well as two orthogonal bending moments can be recorded. The deformations of the specimen during testing can be recorded by two simultaneous high-speed cameras.

***For more information:***

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

Photo: Ole Morten Melgård

*Figure 16 Pendulum accelerator.*

## Pneumatic accelerator

In this test rig, see Figure 17, a projectile with a mass of 50 kg can be accelerated up to a velocity of 25 m/s. The rig consists of an accelerator tube (with an internal diameter of 160 mm) 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 and by double integration 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., Larsen P.K.: *Dropped Objects' Plugging Capacity of Steel Plates: An Experimental Investigation.* International Journal of Impact Engineering, Vol. 9, No. 3, 289-316, 1990.


Photo: Melinda Gaal

*Figure 17* *Pneumatic accelerator.*

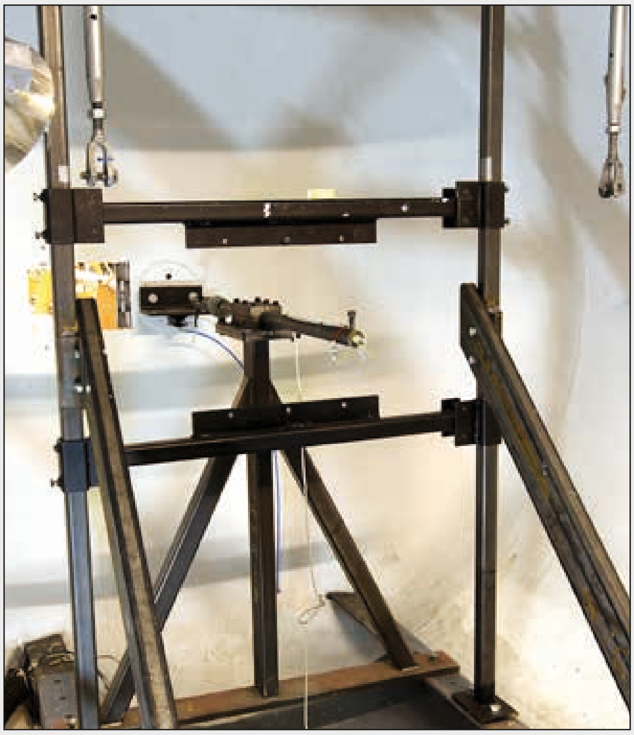


Photo: Melinda Gaal

*Figure 18a* *Compressed gas gun facility.*

## Compressed Gas Gun

A schematic drawing of the compressed gas gun is shown in Figures 18a and 18b. 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 components can be tested full scale. 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.

## Stretch-bending rig

The stretch-bending rig, see Figure 19, 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 servo-hydraulic actuators giving the axial action, and a vertical loading device supported on a servohydraulic actuator. All

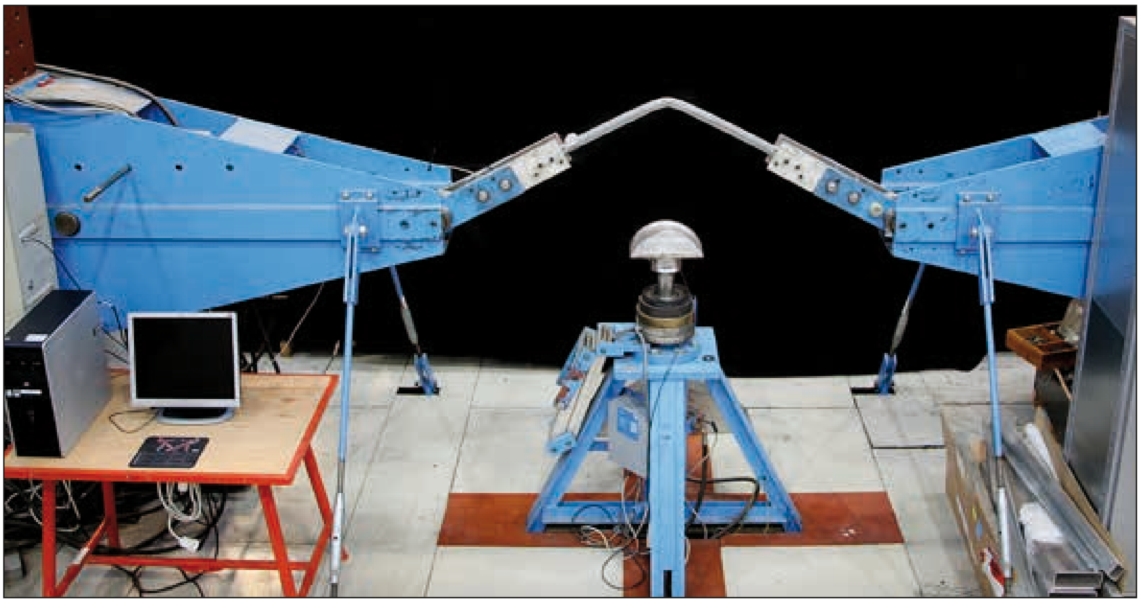


Photo: Melinda Gaal

*Figure 19*
*Stretch-bending rig.*

*Figure 18b   Compressed gas gun facility.*

Photo: Melinda Gaal

After testing, the impact chamber can be opened for final inspection and measurements.

***For more information:***
Børvik T., Langseth M., Hopperstad O.S., Malo K.A.: *Ballistic penetration of steel plates.* International Journal of Impact Engineering 1999; 22: 855-886.
Børvik T., Hopperstad O.S., Langseth M., Malo K.A.: *Effect of target thickness in blunt projectile penetration of Weldox 460 E steel plates.* International Journal of Impact Engineering 2003; 28: 413-464.

actuators have a capacity of 330 kN. The rig has complete instrumentation 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 can be defined.

The rig has been employed in tests where the bending operation of car bumpers is studied. It has also been used to study the behaviour of pipelines subjected to impact and subsequent stretching.

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

Photo: Ole Morten Melgård

*Figure 20 Droptower impact system.*

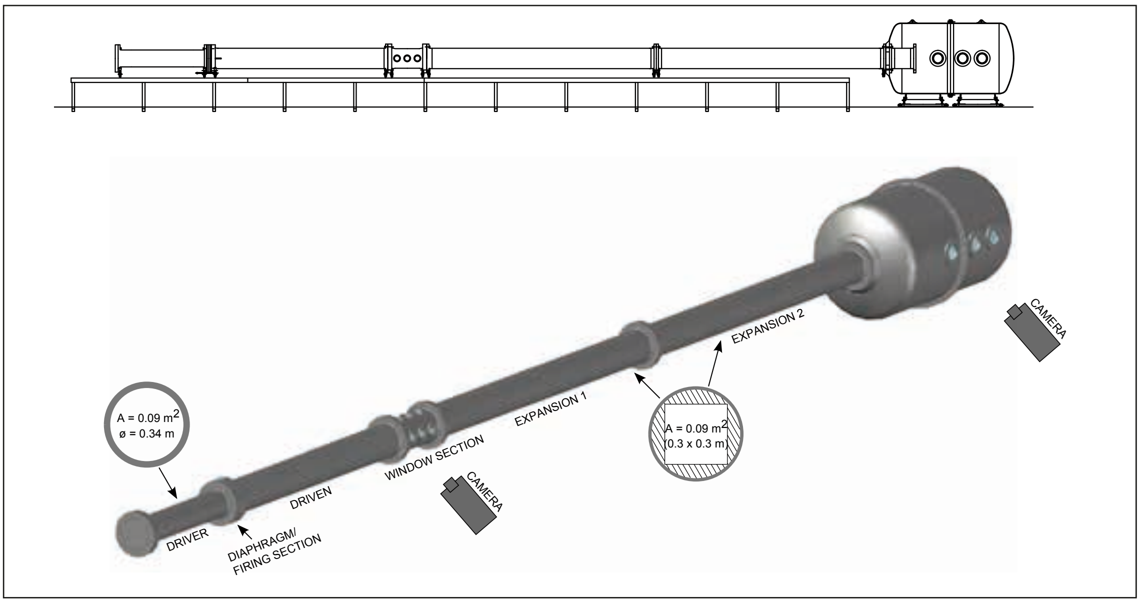
## Droptower impact system

In this machine, see Figure 20, impact testing of materials and small components can be carried out at low and high temperatures. The mass of the projectile ranges from 2-70 kg and gives an impact velocity in the range 0.8-24 m/s. All tests can be carried out with an instrumented nose which gives the impact force as a function of time. The machine has been purchased from Instron and is denoted CEAST 9350.

> ***For more information:***
> www.instron.com

## SIMLab Shock Tube Facility

SIMLab Shock Tube Facility (SSTF) consists of an 18.2 m tube and ends in a 5.1 $m^3$ tank, see Figures 21 and 22. The tube consists of six components, i.e. the driver section, the firing section, the driven section, the window




. Photo: SIMLab, NTNU

*Figure 21*
*Principal sketch of the test facility.*

section and the expansion sections. The tube starts with the driver section which is used to build up high pressure. During rapid release of the compressed gas, a uniform shockwave is generated that propagates down the tube. The driver section has an internal diameter of 0.34 m and is designed to release pressures as high as 170 bar resulting in an incident shock wave with a Mach number of 2.6. The compressed gas is released by a multi-diaphragm system resulting in a controlled and instantaneous burst of the diaphragms, and aluminium inserts may be used to vary the volume of the compressed gas. The rapid and controlled release is ensured by the firing section which consists of a multi-diaphragm system using intermediate pressures to increase the total pressure difference between the driver section and the driven section. The driven section starts with an internal cross-section with a diameter of 0.34 m and is then transformed to a square cross-section of 0.3 m x 0.3 m. This section is 4 m long which ensures a plane/uniform front when the shockwave enters the window section. The window section, see Figure 23, consists of nine windows and threaded holes in the tube floor to enable test specimens to be mounted. The expansion sections are designed to be as long as possible to increase the time window of measurements before secondary reflected waves or rarefaction waves return to the test object. The expansion sections end in the tank which has three windows and an internal diameter of 1.6 m, enabling a variety of test configurations also at the end of the tube, see Figure 24.

Piezoelectric pressure sensors (Kistler 603B) with charge amplifiers (Kistler 5064) and a data acquisition system (National Instruments USB-6356) are used to measure the pressure at 20 locations downstream of the diaphragms. High-speed cameras (Phantom v1610) can be placed next to the window section and the tank to investigate the structural response during the experiment. The pressure measurement can also be synchronized with the high-speed cameras, which enables thorough examination of the entire experiment.

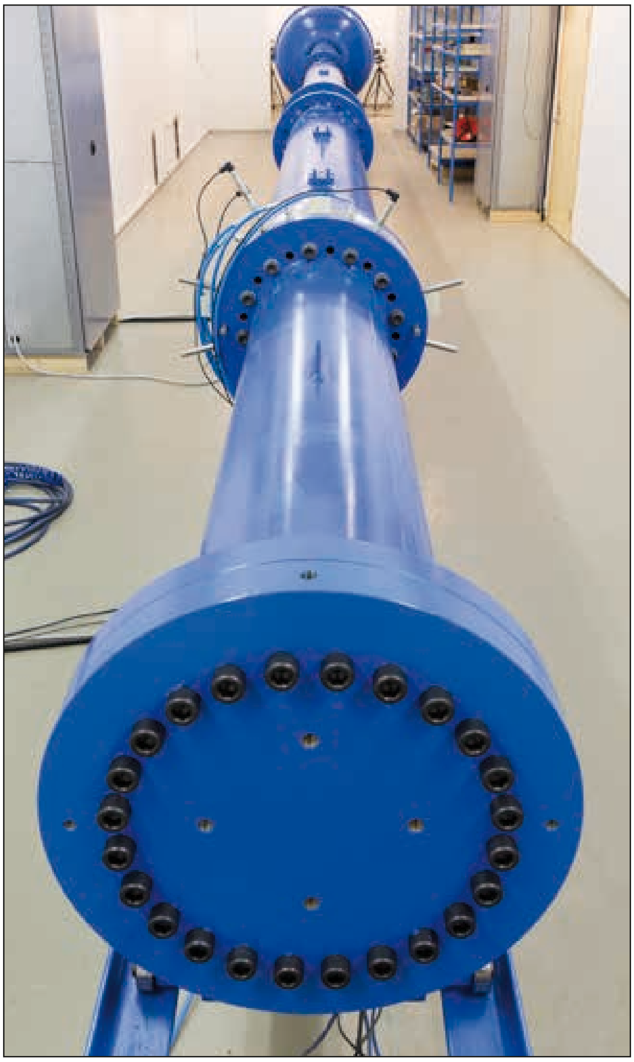


Photo: Ole Morten Melgård

*Figure 22* *View from the driver section down along the tube.*

*Figure 23* *The window section.*

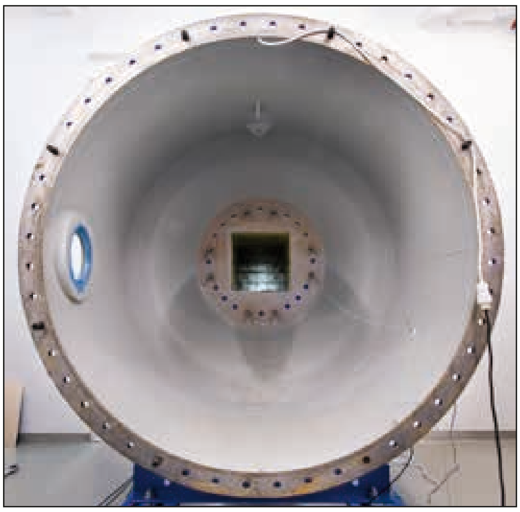


Photo: Ole Morten Melgård

*Figure 24* *Test specimens can be mounted on the end of the tube in the dump tank*

## Joining machine

### Self-piercing riveting machine

In this machine, see Figure 25, self-piercing riveting can be carried out of sheets under industrial conditions. The machine has been purchased from Böllhoff in Germany.

***For more information:***
(http://www.boellhoff.com/en/de/assembly_systems/riveting/rivset.php)

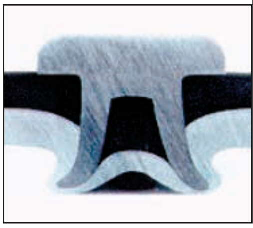



*Figure 25 Self-piercing riveting machine.*

## Infrared camera

The infrared camera shown in Figure 26 (FLIR SC7500) can convert infrared radiation to a visual image that depicts thermal variations across an object or scene. Thus it can be used to measure the surface temperature of a specimen under inelastic deformations. With a resolution of 320×256 pixels the maximum frame rate is 380 per second, while at a resolution of 48×4 pixels the maximum frame rate is 31 800 per second.

***For more information:***
www.flir.com

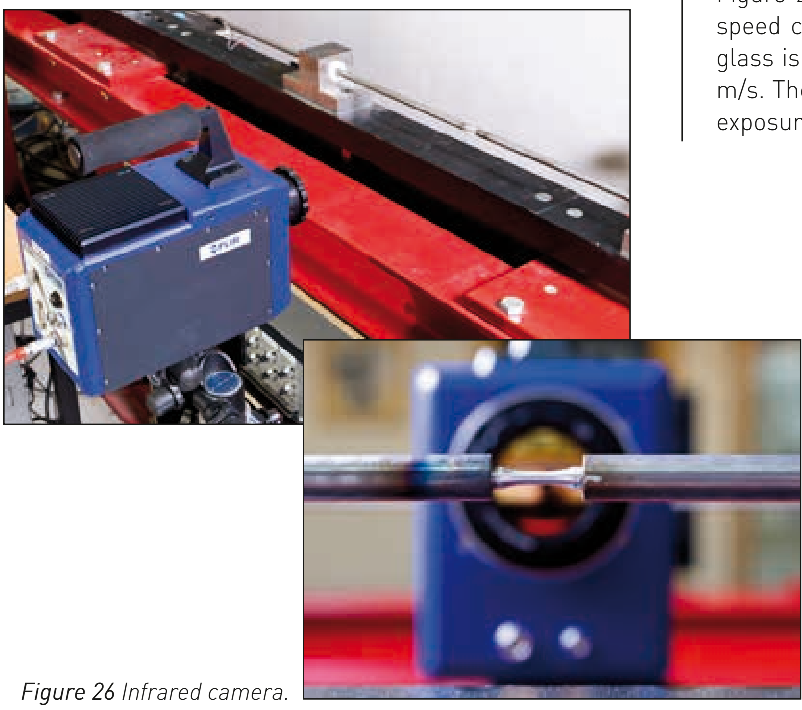


Photo: Ole Morten Melgård

*Figure 26 Infrared camera.*

## High-speed cameras

During impact testing of materials and structures, the events are recorded using high-speed cameras. The research group has access to 2 Photron and 2 Phantom cameras.

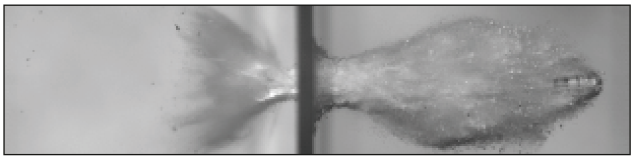


*Figure 27 Impact on laminated glass.*

Figure 27 shows a test where the Phantom V1610 high-speed camera has been used. A 7 mm laminated safety glass is hit by a 7.62 calibre lead bullet at a speed of 800 m/s. The camera is set to a frame rate of 60 000 FPS and exposure time 0.452 μs.

## Cameras for DIC measurements

Two Prosilica GC2450 cameras support the developments of the DIC technique at SIMLab. The cameras have a maximum speed of 15 FPS.

# Visibility

## Workshops and seminars

- SIMLab in cooperation with DNV-GL Oil & Gas organized a workshop on 15 May with the title *Workshop on tensile fracture*. The workshop was part of a concurrent research project with DNV-GL Oil & Gas.

- Assoc. Professor Arne Aalberg and Professor Em. Per Kristian Larsen have given a course on *Design of steel structures in accordance with Eurocode 3* in cooperation with Tekna, a labour union for technical and scientific professionals. The course was given in Oslo on 27 March and 29 October 2014.

## Invited and guest lectures

- Professor Odd Sture Hopperstad was invited to give a lecture at Ecole des Mines in Paris. The lecture was given in cooperation with Professor Ahmed Benallal and had the title *Challenges in the modelling of the behaviour of aluminium alloys for structural applications*.

- Professor Magnus Langseth gave an invited lecture on *Security for structures subjected to extreme loading conditions*. Do we need new knowledge? This was at a seminar on physical security organized by the consultancy company BDO, 18 September 2014, Oslo, Norway.

*DNV-GL Oil & Gas Workshop on 15 May 2014.*

## Keynote lectures

- Professor Magnus Langseth gave a keynote lecture on *Crashworthiness of Aluminium Structures* at the 16th International Conference on Experimental Mechanics ICEM16 on 7-11 July 2014 at University of Cambridge, UK.
- Professor Tore Børvik gave a keynote lecture titled *On the predictability of numerical simulations of ballistic impact* at the 4th International Conference on Impact Loading of Lightweight Structures, 12-16 January 2014, Cape Town, South Africa.
- Professor Odd Sture Hopperstad was invited to give a keynote lecture *On quasi-static and dynamic fracture of high-strength aluminium alloy* at the 20th European Conference on Fracture ECF20, 30 June - 4 July 2014, Trondheim, Norway.
- Professor Magnus Langseth gave a keynote lecture at the 14th International Conference on Aluminium Alloys ICAA14, 15-19 June 2014, Trondheim, Norway. The lecture title was *SIMLab Centre for Research-based Innovation at NTNU*.

## Symposiums and conference sessions

- Professor Odd Sture Hopperstad from SIMLab and Associate Professor Jonas Faleskog from KTH, Stockholm, Sweden organized a mini-symposium on Ductile damage & fracture at the 20th European Conference on Fracture ECF20 on 30 June - 4 July 2014, in Trondheim, Norway.
- Professor Arild Clausen organized a session on polymers at the 16th International Conference on Experimental Mechanics ICEM16 on 7-11 July 2014 in Cambridge, UK.
- Professor Tore Børvik organized a session on steels at the 16th International Conference on Experimental Mechanics ICEM16 on 7-11 July 2014 in Cambridge, UK.

## Awards

- SIMLab's PhD candidate Martin Kristoffersen was awarded the OMAE 2013 Best Paper of Structures, Safety and Reliability Symposium for the paper Damage and failure

## Magazines/Newspapers/TV

- The opening of SIMLab's new Shock tube was broadly covered by Norwegian media:
  VG Nett, Norway's largest newspaper
  Local newspaper Adresseavisen
  Radio report on NRK P1, Norway's largest radio channel
  TV news channel TV2 Nyhetskanalen
  Weekly technical journal Teknisk Ukeblad
  Research magazine Gemini.no
  University newspaper Universitetsavisa
  Online building industry magazines
  Bygg Fakta and Byggeindustrien
  Radio interview on local radio P5
- The opening of the Shock tube was also covered by French online news channels http://www.norvege-fr.com/actualite_norvege.php?id=2193 and http://www.bulletins-electroniques.com/actualites/77077.htm
- The Dean of NTNU's Faculty of Engineering Science and Technology, Ingvald Strømmen, wrote a blog piece about NTNU and SIMLab's initiative for research on physical security. The blog was published on Forskning.no, a Norwegian online magazine for research news.
- Discovery Channel's visit on 3 June was covered by the University newspaper Universitetsavisa and the research magazine Gemini.no.

in an X65 steel pipeline caused by trawl gear impact. The paper was presented at the ASME 32nd Conference on Ocean, Offshore and Arctic Engineering, 9-14 June 2013, Nantes, France.

## Visits

- Discovery Channel Canada visited SIMLab on 3 June to film tests for the programme Daily planet.

*PhD candidate Martin Storheim (in the middle) from SFI SAMCoT explains the test procedure.*

- An article on the Research Council of Norway's web pages looked at the effects of the SFI centre scheme. NTNU in general and SFIs SIMLab and SAMCoT in particular were used to illustrate how the SFI scheme generates cooperation and spin-off effects.

- SIMLab was mentioned in an article on gemino.no and Aftenposten.no. The article dealt with a SINTEF project on modelling of aluminium on the atomic level.

- The need for education and research in the field of structural security was the topic in an article in the technical weekly magazine Teknisk Ukeblad published on 30 October 2014. In the article the Norwegian Defence Estates Agency underlined the need for security as a part of the education of Norwegian engineers and that SIMLab's proposed competence centre for physical security is one way to meet that requirement.

- SIMLab was awarded a new SFI Centre, SFI CASA, on 21 November. This was covered by the local newspaper Adresseavisen, technical weekly Teknisk Ukeblad and dean of NTNU's Faculty of Engineering Science and Technology, Ingvald Strømmen, wrote a blog piece about the new centre: http://forskning.no/blogg/ingvald-strommens-blogg/sfi-suksess

*SIMLab professor Arild Clausen interviewed by Discovery Channel.*

PhD students from SFI SAMCoT, also hosted by NTNU, performed tests on ice in SIMLab's kicking machine facility. The programme was aired on television for viewers in North America on 9 November 2014.

- SIMLab's new test facility, **the Shock tube**, was officially opened on 20 October 2014. In conjunction with the opening a seminar was held with representatives from relevant official authorities in the field of physical security, i.e. the Norwegian National Security Authority, the Norwegian Defence Estates Agency, the Ministry

PhD candidate Vegard Aune explains how the shock tube works.

*The laminated glass after the first official test*

of Local Government and Modernization, Ministry of Justice and Public Security, and the Norwegian Police Security Service. In addition the seminar was attended by representatives from the Research Council of Norway and the Norwegian state's building commissioner Statsbygg. The seminar was entitled *Safety of structures subjected to extreme loading conditions. Do we need new knowledge?* The Shock tube was opened with a first official test and the participants was given a tour in the lab.

*Representatives from NSM look at the shock tube's window section.*

*Inspecting the video of the test in the kicking machine.*

*PhD candidate Vegard Aune presents the test setup.*

*Photos: Øyvind Buljo, NTNU*

# International cooperation

## International cooperation and leading-edge research

International cooperation is one of the success criteria defined by the Research Council of Norway for an SFI centre. For SIMLab, this is taken care of by both international partners as well as strong interaction with universities and research organizations abroad. The latter is mainly initiated by the high quality research carried out by the Centre which is published in peer-reviewed journals as well as the fact that three of the Centre professors are editors in top-level international journals. The international cooperation has resulted in several joint research projects with common publications. Thus, the cooperation with leading international research groups as well as the publication work carried out ensures that the Centre transfers leading-edge technology to the partners and at the same time is able to define new and innovative research areas of importance to the partners.

## Visiting scientists/professors

The following researchers visited SIMLab in 2014:

- Dr Rafael Traldi Moura, University of São Paulo, Brazil. 21 January – 30 June 2014.
- Professor Ahmed Benallal, LMT Cachan, France. 28 January – 9 February 2014 and 14 June – 5 July 2014.
- Researcher at Toyota Motor Europe, Yann Claude Ngueveu, visited SIMLab for a week from 24 to 28 November 2014.

## Research cooperation with organizations

The Centre has strong international cooperation due to its five international partners, i.e. Audi, BMW, Toyota Motor Europe, Renault and SSAB. In addition, the following organizations took an active part in the Centre projects in 2013:

- *Cotutelle agreements for PhD candidates*
  - o LMT-Cachan (Professor Ahmed Benallal), France. Karlsruhe Institute of Technology (Professor Karl Schweizerhof), Germany.
- *Other organizations involved in Centre activities*
  - o University of São Paulo (Professor Marcílio Alves), Brazil. University of Savoie (Professor Laurent Tabourot). Impetus Afea (Dr Lars Olovsson), Sweden. European Commission, Joint Research Centre, Institute for the Protection and Security of the Citizen, Ispra (Dr Folco Casadei), Italy. Texas Institute for Intelligent Materials and Structures (Assoc. Professor Amine Benzerg).

## Guest lectures at SIMLab

The following guest lectures were given at SIMLab in 2014:

- Dr Mike Byfield, University of Southampton, UK and Dr Andy Tyas, University of Sheffield, UK: *Strain rate dependent component based connection modelling for use in the non-linear dynamic analysis of steelwork connections*.
- Daniel Saltzmann and Benjamin J. Meaige, Honda R&D Americas, USA: *Honda's vision over the upcoming years in the area of multi-material joining.*
- PhD Robert Watson, University of Birmingham, UK: *Aluminium casting simulation and its context in the UK*.
- Folco Casadei from Joint Research Centre, Institute for the Protection and Security of the Citizen, Ispra, Italy: *Mesh Adaptivity in Fast Transient Dynamics with Fluid-Structure Interaction.*

# National cooperation

The Centre has ongoing cooperation with Professor Ørjan Fyllingen at the Bergen University College. Graduated as PhD from SIMLab in 2008, he has specialized in how parameter variations can be taken into account in numerical simulations to predict robust behaviour of structures subjected to impact. Ørjan Fyllingen is a co-supervisor for one of the PhD candidates (Espen Myklebust) at SIMLab.

# Students

Students Students

**PhD candidates, post docs and visiting students**
*From left: Dmitry Vysochinskiy, Arne Ilseng, Joakim Johnsen, Miguel Costas, Marius Andersen, Lars Edvard Bryhni Dæhli, Martin Kristoffersen, Egil Fagerholt, David Morin, Mikhail Khadyko, Erik Løhre Grimsmo, Jens Kristian Holmen, Johan Kolstø Sønstabø, Petter Henrik Holmstrøm, Vegard Aune og Vincent Vilamosa.*

Photo: Ole Morten Melgård

## PhD candidates

### The following PhD candidates have been linked to the Centre in 2014:

| Name | Start | Planned exam | Programme | From | Male/Female |
|---|---|---|---|---|---|
| Henning Fransplass* | Spring 2005 | Spring 2014 | C&J | Norway | Male |
| Octavian Knoll* | Summer 2009 | Spring 2015 | F&CP | Germany | Male |
| Marion Fourmeau** | Autumn 2009 | Spring 2014 | F&CP | France | Female |
| Dmitry Vysochinskiy** | Spring 2010 | Autumn 2014 | M4 | Russia | Male |
| Mikhail Khadyko** | Autumn 2010 | Spring 2015 | M4 | Russia | Male |
| Martin Kristoffersen* | Autumn 2010 | Autumn 2014 | OptiPro | Norway | Male |
| Espen Myklebust** | Autumn 2009 | Spring 2015 | F&CP | Norway | Male |
| Marius Andersen* | Autumn 2011 | Autumn 2015 | Polymers | Norway | Male |
| Vincent Vilamosa* | Autumn 2011 | Spring 2015 | M4 | France | Male |
| Vegard Aune** | Autumn 2012 | Autumn 2016 | OptiPro | Norway | Male |
| Lars Edvard Bryhni Dæhli* | Autumn 2013 | Autumn 2017 | F&CP | Norway | Male |
| Erik Løhre Grimsmo** | Autumn 2013 | Autumn 2017 | C&J | Norway | Male |
| Jens Kristian Holmen*** | Autumn 2013 | Autumn 2016 | OptiPro | Norway | Male |
| Petter Henrik Holmstrøm** | Autumn 2013 | Autumn 2017 | Polymers | Norway | Male |

*= Salary and operational costs from the Centre

** = Operational costs from the Centre – salary from other sources

***= Salary and operational cost from other sources

### Related PhD candidates in 2014

- Andreas Koukal is a PhD student at the Technische Universität München. He was recruited by Audi to work on the behaviour and modelling of polymers and is thus linked to the Centre through Audi. Andreas Koukal defended his thesis in June 2014.
- Arne Ilseng works on a PhD project with the working title *Behaviour and modelling of elastomers subjected to a wide range of pressures and temperatures*. The project is under the industrial PhD scheme supported by the Research Council of Norway. Arne Ilseng is employed by Aker Solutions and supervised by personnel from Aker Solutions and SIMLab.
- Johan Kolstø Sønstabø works with SIMLab on a concurrent project funded by Honda R&D Americas. He started his PhD work in August 2013. The project has the title *Behaviour and modelling of flow drilling screws*.
- Joakim Johnsen started as a PhD in August 2014 on a concurrent project on arctic materials. The title of Johnsen's PhD work is *Behaviour and modelling of thermoplastics at low temperatures*.

## Post docs

### The following post docs were linked to the Centre in 2014:

| Name | Start | End | Programme | From | Male/Female |
|---|---|---|---|---|---|
| David Morin | Autumn 2010 | Autumn 2014 | C&J | France | Male |
| Egil Fagerholt | Autumn 2012 | Autumn 2014 | F&CP | Norway | Male |
| Anne Serine Ognedal | Autumn 2012 | Summer 2014 | Polymers | Norway | Female |

## Visiting students

### The following international students have stayed at the Centre in 2014:

- Master's student Hugo Guyard is working as an intern for Audi, Germany, and he visited SIMLab from April to June 2014.
- PhD student Miguel Costas from the University of A Coruña, Spain, started a 6 month stay with SIMLab in October 2014.
- PhD student Robert Watson from the University of Birmingham, UK, visited SIMLab from 10 to 14 November 2014.

## Master's students

### The following master's students (24 male and 4 female students) were associated with the Centre in 2014:

| STUDENT | TOPIC |
|---|---|
| B. Siedziako | Analysis of beam ends with copes |
| B. Hofstad and Hofstad* | Effects of shear layers in steel beams |
| T-A. Knutsen and T. Oma* | Experimental work and stiffness calculation for end-plate joints with hollow sections |
| A.M. Uhre | Hollow section end plate joint |
| S.T. Frølandshagen | Capacity of steel bracket |
| H.A. Nisja | Numerical Modelling of Brittle Failure in Ice Structures |
| B.G. Myrvold and E. Skulstad* | Triangular stiffeners and bracket plates |
| T.A. Hustad and A.L Lindland* | Aluminium structures exposed to blast loading |
| E. Orthe and H. Thorsen* | Ballistic Perforation of Surface Mild Steel Plates |
| E. Digerud and K. Lofthaug* | Bending of X65Offshore Steel Pipes |
| S. Heggelund | Docol 600 DL Steel Plates Subjected to Blast Loading |
| S.M.W. Breivik and E.F. Thomsen* | Perforation of Welded Aluminium Structures |
| H. Frich | Beam-Column Connections Subjected to Static and Dynamic Loading |
| A.H. Amundsen | Behaviour and Modelling of Fibre-Reinforced Polymers |
| G. Båsen and T. Nordgård* | Beam-Column Connections Subjected to Static and Dynamic Loading |
| S. Hegna | Behaviour and modelling of elastomers subjected to a wide spectra of pressures |
| B.M. Kolberg and E.T. Willand* | Behaviour and Modelling of Bolted Connectors in Road Safety Barriers |
| D.H. Amundsen and J.U. Utne* | Behaviour and Modelling of Flow-Drilling Screw Connections |

* Joint thesis

## PhD disputations

**MARION FOURMEAU** defended her thesis on 31 January 2014. The thesis had the title *Characterization of the anisotropic behavior of high-strength aluminium alloy*. The thesis was covered by a Cotutelle agreement between NTNU and ENS-Cachan, Paris and the candidate thus got a degree from both institutions. Her supervisors were Professor Tore Børvik and Professor Odd Sture Hopperstad from Department of Structural Engineering, NTNU and Professor Ahmed Benallal from ENS-Cachan, Paris, France. The assessment committee consisted of the following persons: Professor Thomas Pardoen from Université catholique de Louvain, Belgium and Professor John Botsis from Ecole Polytechnique de Lausanne, Switzerland. Aase Reyes from NTNU acted as administrator of the committee.

**PhD disputation for Marion Fourmeau – the committee.** *From the left: Thomas Pardoen, Marion Fourmeau, Aase Reyes and John Botsis.*

**HENNING FRANSPLASS** defended his thesis on 13 February 2014. The topic of his thesis was *Behaviour of threaded steel fasteners at elevated deformation rates*. His supervisors were Professor Magnus Langseth and Professor Odd Sture Hopperstad, both from Department of Structural Engineering, NTNU. The assessment committee had three members: Professor Em. Preben Terndrup Pedersen from the Technical University of Denmark, Knut Erling Moen from SINTEF Raufoss Manufacturing and the committee's administrator Professor Arne Aalberg from Department of Structural Engineering, NTNU.

**PhD disputation for Henning Fransplass – supervisors and the committee.** *From the left: Arne Aalberg, Knut Erling Moen, Preben Terndrup Pedersen, Henning Fransplass, Magnus Langseth and Odd Sture Hopperstad*

MARTIN KRISTOFFERSEN defended his thesis on 11 December 2014. The topic of Martin's thesis was *Impact on X65Offshore Pipelines*. Supervisors were professors Tore Børvik, Odd Sture Hopperstad and Magnus Langseth, all from Department of Structural Engineering, NTNU. The assessment committee consisted of Professor Carlos Guedes Soares from Universidade de Lisboa, Portugal, Professor Preben Terndrup Pedersen from the Technical University of Denmark, and Professor Kjell H. Holthe from Department of Structural Engineering at NTNU who acted as the committee's administrator.

**PhD disputation for Martin Kristoffersen – supervisors and the committee.**
*From the left: Odd Sture Hopperstad, Kjell H. Holthe, Preben Terndrup Pedersen, Martin Kristoffersen, Carlos Guedes Soares and Magnus Langseth*

DMITRY VYSOCHINSKIY defended his thesis on 16 December 2014. Dmitry's thesis had the title *Formability of aluminium alloy subjected to prestrain by rolling*. His supervisors were Professor Aase Reyes from the Department of Structural Engineering, NTNU, and Odd-Geir Lademo who is Adjunct Professor at the Department of Structural Engineering at NTNU and Research Director at SINTEF Materials and Chemistry. The assessment committee had three members: Professor Dorel Banabic from the Technical University of Cluj-Napoca, Romania, Dr. Alan Leacock from University of Ulster, UK, and Assoc. Professor Arne Aalberg from the Department of Structural Engineering, NTNU. Arne Aalberg was the administrator of the committee.

**PhD disputation for Dmitry Vysochinskiy – supervisors and the committee.**
*From the left: Dorel Banabic, Dmitry Vysochinskiy, Aase Reyes, Alan Leacock, and Arne Aalberg. Odd-Geir Lademo was not present.*

# 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 RCN 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 2014 are shown below. The numbers for the wind-up of the Centre in the period 2015-2017 are included in these numbers for 2014.

**SIMLab: Funding 2014** (All figures in 1000NOK)

| | | State aid | | | Industry | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Research Programmes | Type of research | RCN Grant | Host (NTNU) | SINTEF | NDEA | NPRA | AUDI | BMW | Renault | Toyota | Statoil | SSAB | Benteler | Hydro | Total State Aid | Total Funding | State aid/ total funding |
| C & J | F | 1504 | 336 | | | 870 | | | | | | | | | 1840 | 2710 | 0.68 |
| C & J | I | | | | | | | | | | | | | | | | |
| F&CP | F | 2883 | 734 | | | | 100 | | | | | | | 900 | 3617 | 4617 | 0.78 |
| F&CP | I | | | | | | | | | | | | | | | | |
| $M^4$ | F | 985 | 234 | 1100 | | | | | | | | | | 2000 | 2319 | 4319 | 0.54 |
| $M^4$ | I | | | | | | | | | | | | | | | | |
| OptiPro | F | 1099 | 734 | | 1350 | | | | | | | | | | 1833 | 3183 | 0.58 |
| OptiPro | I | | | | | | | | | | | | | | | | |
| Poly | F | 1314 | 1595 | | | | 100 | | 200 | | | | | | 2909 | 3209 | 0.91 |
| Poly | I | | | | | | | | | | | | | | | | |
| Demo | F | | 801 | | | | | | | | | | | | 801 | 801 | 1 |
| Demo | I | | 100 | | 108 | 108 | 408 | 108 | 408 | 108 | 108 | 408 | 308 | 508 | 100 | 2680 | 0.04 |
| Equipment | | 2592 | | | 379 | 9 | 90 | 90 | 114 | 90 | 90 | 90 | 14 | | 2592 | 3588 | |
| Adm | | 891 | 1000 | | 363 | 133 | 302 | 302 | 278 | 302 | 452 | 302 | 178 | 692 | 1891 | 5195 | |
| Total | | 11268 | 5534 | 1100 | 2200 | 1120 | 1000 | 500 | 1000 | 500 | 650 | 800 | 500 | 4100 | 17902 | 30272 | |

F = Fundamental research, I = Industrial research

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

**SIMLab: Cost 2014** (All figures in 1000NOK)

| Research Programmes | Host (NTNU) | SINTEF | NDEA | NPRA | AUDI | BMW | Renault | Toyota | Statoil | SSAB | Benteler | Hydro | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C & J | 1540 | 300 | | 870 | | | | | | | | | 2710 |
| F&CP | 3317 | 1000 | | | 100 | | | | | | | 200 | 4617 |
| $M^4$ | 1219 | 1100 | | | | | | | | | | 2000 | 4319 |
| OptiPro | 1683 | 300 | 1200 | | | | | | | | | | 3183 |
| Poly | 2659 | 250 | | | 100 | | 200 | | | | | | 3209 |
| Demo | 1201 | 780 | | | 300 | | 300 | | | 300 | 200 | 400 | 3481 |
| Equipment | 3558 | | | | | | | | | | | | 3558 |
| Adm | 4746 | 449 | | | | | | | | | | | 5195 |
| Total | 19923 | 4179 | 1200 | 870 | 500 | 0 | 500 | 0 | 0 | 300 | 200 | 2600 | 30272 |

# Publications

The following lists journal publications and conference contributions generated from the Centre in 2014:

## Journal publications


1. Børvik T., Dey S., Olovsson L.: *Penetration of granular materials by small-arms bullets*. International Journal of Impact Engineering 75 (2015) 123-139.
2. Børvik T., Marken L.A., Langseth M., Hopperstad O.S., Rørvik G.: *Impact behaviour of duplex stainless steel pipe fittings: influence of sigma phase precipitation.* Ships and Offshore Structures (2014) DOI: 10.1080/17445302.2014.954303.
3. Forrestal M.J., Børvik T., Warren T.L., Chen W.: *Perforation of 6082-T651 Aluminum Plates with 7.62 mm APM2 Bullets at Normal and Oblique Impacts.* Experimental Mechanics 54: 3 (2014) 471-481.
4. Fransplass H., Langseth M., Hopperstad OS.: *Experimental and numerical study of threaded steel fasteners under combined tension and shear at elevated loading rates*. International Journal of Impact Engineering 76 (2015) 118-125.
5. Fyllingen Ø., Langseth M., Hopperstad O.S.: *Investigation of high-strength steel component subjected to stretch-bending: effect of forming history.* Key Engineering Materials 611-612 (2014) 1702-1709.
6. Hoang, N-H., Langseth M.: *Aluminium Self-Piercing Rivet's Failure: Testing and Numerical Analyses.* Applied Mechanics and Materials 541-542 (2014) 1355-1359.
7. Khadyko M., Dumoulin S., Børvik T., Hopperstad O.S.: *An experimental-numerical method to determine the work-hardening of anisotropic ductile materials at large strains*. International Journal of Mechanical Sciences 88 (2014) 25-36.
8. Kristoffersen M., Casadei F., Børvik T., Langseth M., Hopperstad O.S.: *Impact against empty and water-filled X65 steel pipes - Experiments and simulations.* International Journal of Impact Engineering 71 (2014) 73-88.
9. Ognedal A.S., Clausen A.H., Berstad T., Seelig T., Hopperstad O.S.: *Void nucleation and growth in mineral-filled PVC - An experimental and numerical study.* International Journal of Solids and Structures 51:7-8 (2014) 1494-1506.
10. Ognedal A.S.: Clausen A.H., Dahlen A., Hopperstad O.S.: *Behavior of PVC and HDPE under highly triaxial stress states: An experimental and numerical study.* Mechanics of Materials 72 (2014) 94-108.
11. Rakvåg K.G., Børvik T., Hopperstad O.S.: *A numerical study on the deformation and fracture modes of steel projectiles during Taylor bar impact tests*. International Journal of Solids and Structures 51:3-4 (2014) 808-821.
12. Vautrot M., Balland P., Hopperstad O.S., Tabourot, L., Raujol-Veille J., Toussaint F.: *Experimental Technique to Characterize the Plastic Behaviour of Metallic Materials in a Wide Range of Temperatures and Strain Rates: Application to a High-Carbon Steel.* Experimental Mechanics 54:7 (2014) 1163-1175.
13. Vilamosa V., Clausen A.H., Fagerholt E., Hopperstad O.S., Børvik T.: *Local measurement of stress-strain behaviour of ductile materials at elevated temperatures in a split-Hopkinson tension bar system*. Strain 50:3 (2014) 223-235.
14. Westermann I., Pedersen K.O., Furu T., Børvik T., Hopperstad O.S.: *Effects of particles and solutes on strength, work-hardening and ductile fracture of aluminium alloys*. Mechanics of materials 79 (2014) 58-72.
15. Zhang K., Holmedal B., Dumoulin S., Hopperstad O.S.: *An explicit integration scheme for hypo-elastic viscoplastic crystal plasticity*. Transactions of Nonferrous Metals Society of China 24:7 (2014) 2401-2407.
16. Zhang K., Holmedal B., Hopperstad O.S., Dumoulin S.: *Modelling the plastic anisotropy of aluminium alloy 3103 sheets by polycrystal plasticity models*. Modelling and Simulation in Materials Science and Engineering 22 (2014) 075015.
17. Zhang K., Holmedal B., Hopperstad O.S., Dumoulin S., Gawad J., Van Bael A., Van Houtte P.: *Multi-level Modelling of Mechanical Anisotropy of Commercial Pure Aluminium Plate: Crystal Plasticity Models, Advanced Yield Functions and Parameter Identification.* International Journal of Plasticity DOI: 10.1016/j.ijplas.2014.02.003
18. Zhang K., Hopperstad O.S., Holmedal B., Dumoulin S.: *A robust and efficient substepping scheme for the explicit numerical integration of a rate-dependent crystal plasticity model*. International Journal for Numerical Methods in Engineering 99:4 (2014) 239-262.

## Keynote lectures

- Langseth M.: *Crashworthiness of Aluminium Structures.* The 16th International Conference on Experimental Mechanics ICEM16, 7-11 July 2014, Cambridge, UK.
- Børvik T.: *On the predictability of numerical simulations of ballistic impact.* The 4th International Conference on Impact Loading of Lightweight Structures, 12-16 January 2014, Cape Town, South Africa.
- Hopperstad O.S.: *On quasi-static and dynamic fracture of high-strength aluminium alloy.* The 20th European Conference on Fracture ECF20, 30 June - 4 July 2014, Trondheim, Norway.
- Langseth M.: *SIMLab Centre for Research-based Innovation at NTNU*. The 14th International Conference on Aluminium Alloys ICAA14, 15-19 June 2014, Trondheim, Norway.

## Invited lectures

- Hopperstad, O.S.: *Challenges in the modelling of the behaviour of aluminium alloys for structural applications.* Ecole des Mines, 22 May 2014, Paris, France.
- Langseth M.: *Security for structures subjected to extreme loading conditions. Do we need new knowledge?* BDO, 18 September 2014, Oslo, Norway.

## Conference contributions

1. Andersen M., Clausen A.H., Hopperstad O.S.: *Large strain measurement of polymers subjected to uniaxial loading using digital image correlation and edge tracing*. The 16th International Conference on Experimental Mechanics ICEM16, 7-11 July 2014, Cambridge, UK.
2. Forrestal M.J., Warren T.L., Børvik T.: *A scaling law for APM2 bullets and aluminum armor.* Dynamic Behavior of Materials 1 (2014), 297-300, Conference Proceedings of the Society for Experimental Mechanics Series.
3. Gruben G., Fagerholt E., Hopperstad O.S., Børvik T., Langseth M.: *Numerical simulation of ductile fracture in modified Arcan test*. The 20th European Conference on Fracture ECF20, 30 June - 4 July 2014, Trondheim, Norway.
4. Hopperstad OS, Westermann I, Pedersen KO, Furu T, Børvik T. *Influence of processing route on the work-hardening and ductile fracture of an AA6060 aluminium alloy*. Proceedings of the 14th International Conference on Aluminium Alloys, 15-19 June, 2014, Trondheim, Norway.
5. Hopperstad O.S., Børvik T., Fourmeau M., Pedersen K.O., Benallal A.: *Quasi-static and dynamic fracture of high-strength aluminum alloy.* Proceedings of 20th European Conference on Fracture, June 30 – July 4, 2014, Trondheim, Norway.
6. Hopperstad OS, Pedersen KO, Westermann I, Børvik T. *Effects of microstructure and stress triaxiality on the ductile fracture of aluminium alloys*. Proceedings of EMMC14 – European Mechanics of Materials Conference, 27-29 August, 2014, Gothenburg, Sweden.
7. Khadyko M., Dumoulin S., Hopperstad O.S.: *Slip system interaction matrix and its influence on the macroscopic response of Al alloys*. The 14th International Conference on Aluminium Alloys ICAA 14, 15-19 June 2014, Trondheim, Norway.
8. Kristoffersen M., Børvik T., Langseth M., Hopperstad O.S.: *Fracture in X65 pipeline steel*. The 20th European Conference on Fracture ECF20, 30 June - 4 July 2014, Trondheim, Norway.
9. Kristoffersen M, Børvik T, Hopperstad OS, Langseth M. *Damage and fracture in X65 steel pipes subjected to impact loads*. Proceedings of EMMC14 – European Mechanics of Materials Conference, 27-29 August, 2014, Gothenburg, Sweden.
10. Nordhagen H., Dumoulin S., Gruben G.: *The ductile fracture velocity in pressurized pipelines: a numerical study*. The 20th European Conference on Fracture ECF20, 30 June - 4 July 2014, Trondheim, Norway.
11. Rakvåg K.G., Børvik T., Hopperstad O.S.: *Deformation and fracture of steel projectiles during Taylor bar impact tests*. Proceedings of the 16th International Conference on Experimental Mechanics, ICEM16, 7-11 July, 2014, Cambridge, UK.
12. Rakvåg K.G., Christensen S.O., Børvik T.: *Fragmentation of steel casings.* Proceedings of 23rd International Symposium on Military Aspects of Blast and Shock (MABS23), 7-12 September, 2014, Oxford, UK.
13. Sønstabø J.K., Holmstrøm P.H., Morin D., Langseth M.: *Behaviour of Flow-Drilling Screw connections*. The 14th International Conference on Aluminium Alloys ICAA 14, 15-19 June 2014, Trondheim, Norway.
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# Notes

Annual Report for SIMLab Centre for Research-based Innovation2014

Skipnes Kommunikasjon Nordic ecolabel - printed matter Lisence no. 241 731

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