FAILURE MECHANICS OF POLYMERIC FOAM CORES FOR SANDWICH STRUCTURES

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Keywords: Polymeric Foam, Marine, Transportation, Impact, Finite Element Analysis

Abstract
Polymeric foams are widely used as a core material in sandwich structures. For applications subject to impact loads such as marine vessels, road and rail transportation and sporting equipment the toughness and energy absorption of the foam materials are important characteristics. The complex microstructure of polymeric foam core materials means that their deformation and failure processes are particularly difficult to predict and simulate. The primary focus of this work is to characterize and understand the damage and failure mechanisms in polymeric foam cores, particularly those subjected to impact loads. The results from these studies are being used to establish and validate constitutive models for the foam materials. Quasi-static and dynamic testing has been undertaken of material coupons and sandwich panel structures for a range of polymeric foam types. This includes through thickness compression, four-point loaded sandwich beams and hard-body impact of sandwich panels. Implicit FEA models have been developed for material coupon cases and Explicit FEA models of sandwich beams and panels have been developed for impact loadings. The models have demonstrated the complexity of the stress and strain fields for both load cases, and the limitations of classical foam constitutive models.

1. Introduction

Polymeric foams are widely used as a core material in sandwich structures. For applications subject to impact loads such as marine vessels, road and rail transportation and sporting equipment the toughness and energy absorption of the foam materials are important characteristics. The complex microstructure of polymeric foam core materials means that their deformation and failure processes are affected by both their local microstructure, and the constitutive behavior of the base polymer. This makes prediction of their failure mechanics particularly difficult. The macroscopic properties of the foam are determined by the polymer constitutive behavior, cell wall thickness, size distribution and shape of the cellular structure [1]. In most applications of sandwich structures the facesheets usually carry the in-plane and bending loads, whereas the core carries the out of plane shear, and the through thickness compressive loads. Correct characterisation of failure modes is critical, as failure can occur in one or multiple forms, where one failure mode can trigger others [2,3]. Transverse shear failure of the core is a common failure mode for sandwich structures, particularly under transverse impact loads from water slamming [4] or hard-body impact [5]. The rate at which loads are applied to polymeric foam structures has a large effect on their performance, with the strength of most core materials changing significantly with loading rate [6]. The general trend is that increasing the loading rate increases the shear strength of the material, up to a certain rate and that higher rates result in more brittle like failures. These effects differ greatly between different formulations of polymeric foams [6].

The primary focus of this work is to characterize and understand the damage and failure mechanisms in polymeric foam cores, particularly those subjected to impact loads. The results from these studies are being used to establish and validate constitutive models that can include the required orthotropy, rate and temperature dependencies. Quasi-static and dynamic testing has been undertaken of material coupons and sandwich panel structures for a range of polymeric foam types. This includes through thickness compression, four-point loaded sandwich beams and hard-body impact of sandwich panels. Implicit FEA models have been developed for material coupon cases and Explicit FEA models of sandwich beams and panels have been developed for impact loadings. Results have been used to investigate the ability of alternative numerical foam plasticity models to capture the yield and post-yield plasticity behaviour of the materials.

2. Materials and Specimens

2.1. Materials

Foam core materials used in this study were Polyvinyl Chloride (Gurit PVC100, PVC130), Styrene-Acrylonitrile (Gurit SAN100, SAN130), and Polyethylene Terephthalate (Gurit PET90), with nominal densities of 90, 100 and 130 kg/m^3, as denoted by their names. Facesheets varied depending on the test type. For the through thickness compression tests these were tested with and without resin infused 825 gsm fiberglass/epoxy (Gurit PrimeTM 20LV) facesheets. For the beam and panel tests the facesheets comprised of eight layers of 500 gsm unidirectional glass fibre layers (Colan MU 4500 G) in a symmetric (0/90)n sequence with the same resin system. The beam and panel specimens also had a 5mm thick internal ferrite layer of grade Y30BH, due to their application for automotive inductive power transfer [5].

2.2. Specimen Construction.

The primary thickness compression specimens had in-plane dimensions of 60mm x 60 mm and thicknesses of 17.1mm without facesheets and ~32mm with face sheets. The four point beam and panel specimens had 3.1mm face sheets (top and bottom), 7mm PET90 foam and 5mm of ferrite. The sandwich beams had lengths of approximately 400mm, widths of 40mm and the panels for impact testing had external dimensions of 400x400mm. Through thickness compression testing was also undertaken of 50mm x 50 mm blocks of the same construction as the beams and panels.

3. Testing Methods

3.1. Through Thickness Compression

The compression tests were carried out based on the ASTM D1621 standard as shown in Figure 1. The standard specifies a cross head speed which compresses the sample at a rate of 10% of the current thickness per minute, resulting in a cross head speed of 1.71 mm per minute without facesheets and 3.15 mm per minute with facesheets. Pre-load of 50 N was applied and the testing continued until the foam was compressed to 80% of its original thickness. In order to capture localised strain, full-field Digital Image Correlation (DIC) was used with the resulting strain fields being used to identify regions of elastic and plastic strain and densification occurring at different times at various regions in the specimen. Capturing strain values through DIC allowed for accurate stress-strain data to be developed, post-processed and used as inputs for the FE models. The post-processing included both investigations of overall and local strain distributions on the surface of the foam blocks.

3.2. Four Point Beam Testing

Four point bending tests were conducted for each beam until failure as shown in Figure 2. Rubber pads of thickness 5 mm were used at each support to avoid premature failure due to local loads. The supports were 300 mm apart, with an inner span of 100 mm. Uniaxial strain gauges (type EA-13-120LZ-120) were applied in the center of the top and bottom face of the beam.

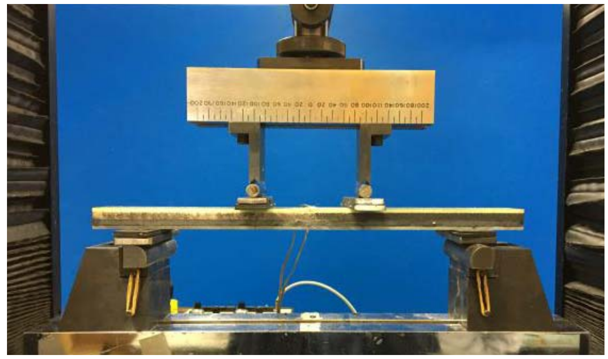

Figure 1. Compression testing setup with DIC cameras. **Figure 2.** Four point loaded beam test setup.

3.3. Panel Impact Testing

The panels were clamped in a custom made fixture within an Imatek IM10 drop weight impact testing facility, as shown in Figure 3. The drop tower was fitted with a 16.24 kg 90 mm diameter hemispheric striker with an 8.52 kg carriage resulting in a total impactor mass of 24.77 kg. The Imatek IM10 instrumentation system measured the impact force and the velocity and position at the start of the impact event. From this, the impactor acceleration, velocity, displacement and energy was derived. An additional LCIT displacement transducer was used for measuring the exterior facesheet displacement at the bottom center position. Strain gauges (FLA-3-350-11 from Tokyo Sokki Kenkyujo Co.) were applied at multiple positions to the panel surface, and embedded either side of the ferrite layer within the panel. The impact events were filmed with a Phantom VEO 410L high-speed camera at a rate of 5200 frames per second. In addition to qualitative information about the impact event this also provided validation of the impactor velocity and displacements, and through tracking reference points on the internal edges of the test fixture enabled quantification of any boundary deformations.

Figure 3. Panel impact test facility.

4. Simulation Methods

4.1. Through Thickness Compression Simulation

The through thickness compression was modelled using the Abaqus 6.14-2 non-linear implicit solver and a general purpose linear brick element (type C3D8R). The constitutive models included Isotropic Elastic-Perfectly Plastic, Hyperfoam and Crushable Foam models. For the Elastic-Perfectly Plastic case the Young's modulus and shear modulus were taken from were sourced from the Gurit data sheet and the Poisson's ratio calculated from those. Hyperfoam required three inputs of a stiffness value, large strain behaviour and a Poisson's ratio. Values for these inputs were found from data sheets as well as from literature useage of related Hyperfoam models. The Crushable Foam model required two parameters defining the plastic region, the compression yield stress ratio and the hydrostatic yield stress ratio which were taken to be 1.1 and 0.1 respectively from previous crushable foam models. The additional sub option of crushable foam hardening required the two inputs of yield stress and uniaxial plastic strain. These two inputs require stress and strain data after the point of plasticity which were derived from the compression test DIC data.

4.2. Four Point Beam Simulation

The beam FE model, Figure 4, was set up using a dynamic explicit single step model in Abaqus 6.14-2. The model was modelled in 3D as one element thick using C3D8R elements. Symmetry in the vertical plane at the center of the beam was employed to reduce the size of the mesh and hence reduce the computational expense. The model consists of four distinct parts: the top cylinder, bottom cylinder, rubber/steel pads and sandwich beam. Both the top and bottom cylinder were set up as discrete rigid surfaces. The top and bottom cylinders had radii of 5 and 10 mm respectively. The rubber and steel pads were modelled using a single deformable part of height 10 mm and width 30 mm with two 3 mm radii at each edge of the rubber. The half beam was modelled as a single rectangular prism of length 200 mm, height 18 mm and depth 1 mm. It was partitioned three times horizontally at 3 mm, 8 mm, and 15 mm from the bottom face dividing it into four distinct regions corresponding to the four layers of the sandwich structure. The ferrite layer was further partitioned vertically at 50 mm and 150 mm from the plane of symmetry dividing the ferrite into its component tiles. Two additional partitions were created to model the interlayer of epoxy which separates the ferrite tiles. The GFRP facesheets were modelled using an orthotropic linear elastic material model with material properties as follows: $E_x = E_z = 18000$ MPa, $E_y = 4000$ MPa, $\nu_{xy} = \nu_{xz} = \nu_{yz} = 0.3$, $G_{xz} = G_{yz} = 3000$ MPa, and $G_{xy} = 3200$ MPa. Four different material models were used for the GPET90 foam; Linear Elastic Isotropic, Linear Elastic Perfectly Plastic Isotropic, Hyperfoam, and the Abaqus Crushable Foam material model. The Linear Elastic, Linear Elastic Perfectly Plastic, and Crushable Foam models all had a linear elastic constitutive relation for small strains with a Young's Modulus of $E = 95$ MPa. The yield stress used for the Linear Elastic Perfectly Plastic model was 1.27 MPa. The Hyperfoam material model's constitutive model was calculated internally by Abaqus using regression to stress strain data gathered by the uniaxial compression tests previously performed in this work. The plastic and densification region of the Crushable Foam model was also specified using the test compression data

4.3. Panel Impact Simulation

The sandwich panel FE model, Figure 5, used x and y direction symmetry to minimise model size and computational cost. The test fixture was included in the model to capture boundary deformations as observed in the testing. Several internal partitions were created to improve mesh quality by reducing mesh skewness and increasing the regions with structured meshes. Cylindrical partitions were created around the bolt holes to create a surface with which to apply bolt clamping loads. All parts were meshed using C3D8R elements. The same material constitutive models were used for this case as for the beams. The impactor component had specified mass and initial velocities to create the required energy levels to match the experiments.

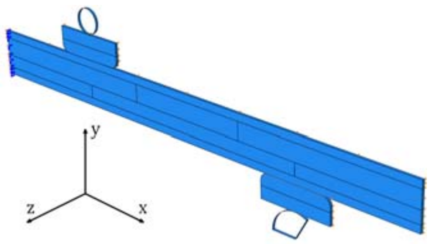

Figure 4. Four point loaded beam model.

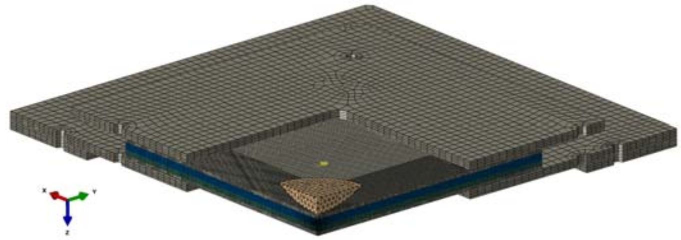

Figure 5. Quarter panel impact model with fixtures.

5. Results

5.1. Through Thickness Compression

Figure 6 shows the DIC strains at increasing average compression strains for SAN 100 and PVC 100 foam specimens with facesheets during a compressive test. The regions of strain localisation and initiation of yield are very different between the foam types, highlighting the effects of different inhomogeneity within the different cores. When modelled using the Crushable Foam constitutive model in ABAQUS the compressive stress-strain correlated well with the experiments (Figure 7), however the model did not accurately simulate tensile and shear behaviour in beams, limiting its applicability in more realistic loading scenarios such as a transversely loaded beam or panel.

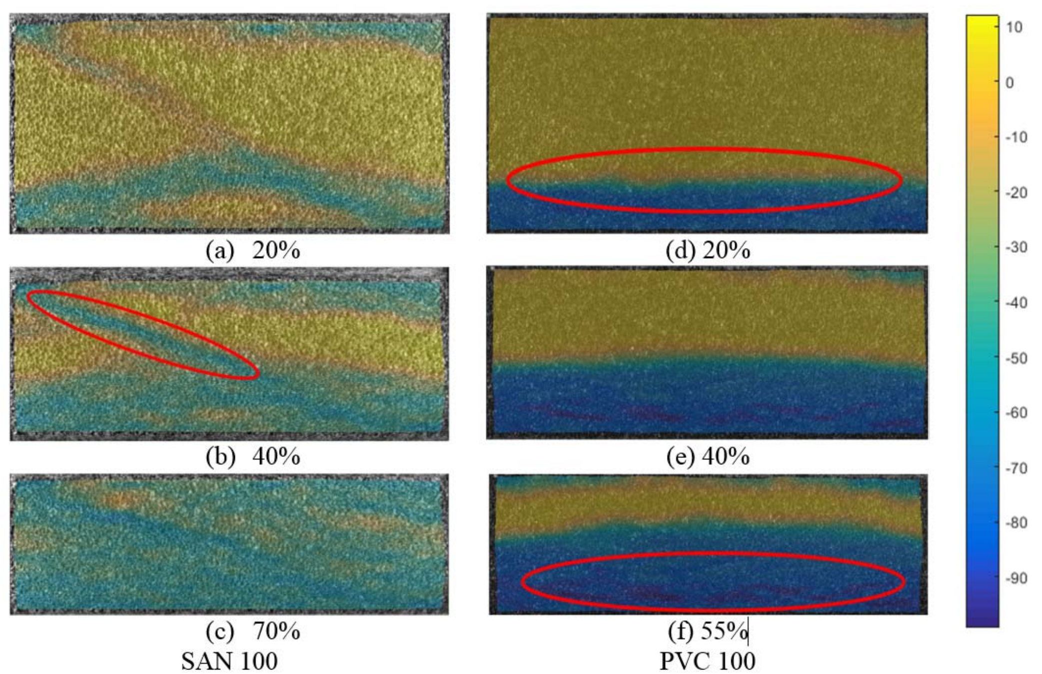

Figure 6. DIC strain results for SAN and PVC foam during through thickness compression tests (%).

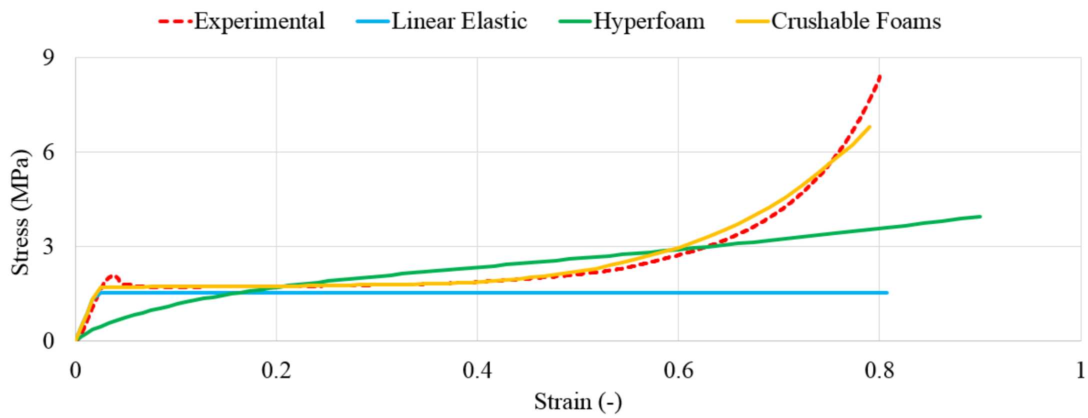

Figure 7. Compressive stress-strain comparison between experiment and FEA.

5.2. Four Point Beams

Figure 8 shows the relationship between the experimental beam deflection and flexural load and the FE model using a Crushable Foam, Hyperfoam, Linear Elastic, and the Linear Elastic Perfectly Plastic foam material models. The Crushable Foam, Linear Elastic, and Linear Elastic Perfectly Plastic models all use the same flexural stiffness for low deflections. This is due to their foam models having identical elastic responses for small strains. They all have higher initial flexural stiffness than observed in the experiments which may be due to differences in the actual material's Young's Modulus compared to the supplier datasheet. The Hyperfoam material model is back calculated by Abaqus from the experimental compression data. The behavior here is similar to that for the compression modelling where this model under predicts stiffness for small strains. As expected the Linear Elastic model follows an essentially linear load to deflection curve causing it to deviate considerably from the experiment. The Linear Elastic Perfectly Plastic model appears initially stiffer than the experiment but yields in a similar way to the experiment but at a higher flexural load and is stiffer than the experiment during the post yield region (4 to 10 mm). The Crushable Foam model is initially stiffer than the experiment, yields at a similar flexural load then again appears slightly stiffer than the experiment during the post yield region (4 to 10 mm deflection). At larger deflections than those shown here the Crushable Foam model did not perform as well because it does not accurately model tensile failure modes, and hence is limited in its capabilities for large shear deformations.

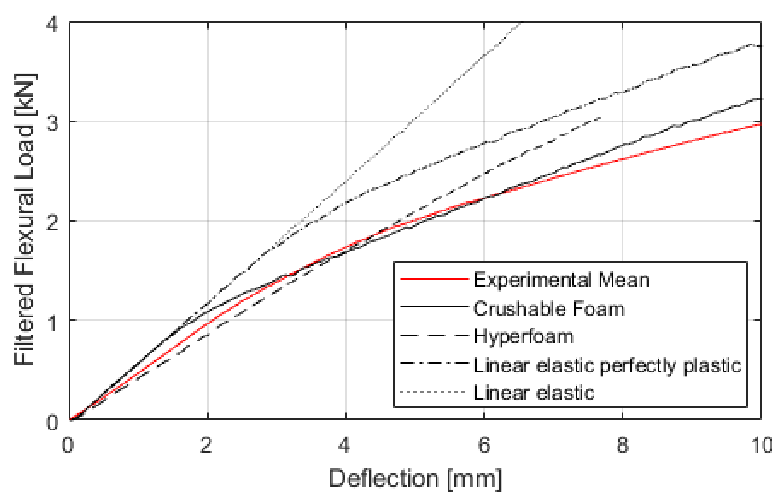

Figure 8. Sandwich beam load-deflection comparison between experiment and FEA.

5.3. Panel Impacts

Figure 9 presents front and back-face transverse deformations of the sandwich panel during hard-body impacts at different energies. Results include experimental, FEA (with the Hyperfoam constitutive model) and an analytical solution [5]. In comparison to the tests, the results of the FEA analysis show almost the same front face deflections up to approximately 120 J, but under-predict the deflections above this. The back face deflections of the FEA-analysis are lower than the experiments over all energies. For the energies above 200 J the deflection is underestimated by the FEA-model, which may be related to the lack of face-sheet damage modelling in the FEA. Figure 10 shows typical displacement contours during an impact, highlighting the large local deformations in the local region of the impact. In some cases, there was up to 85% apparent through thickness strain at the panel center. This was unexpected as most of these foams reach full consolidation at approximately 50 to 60% compressive strain, however the FEA models demonstrated that there was substantial in-plane plastic strains of the foam away from the central region.

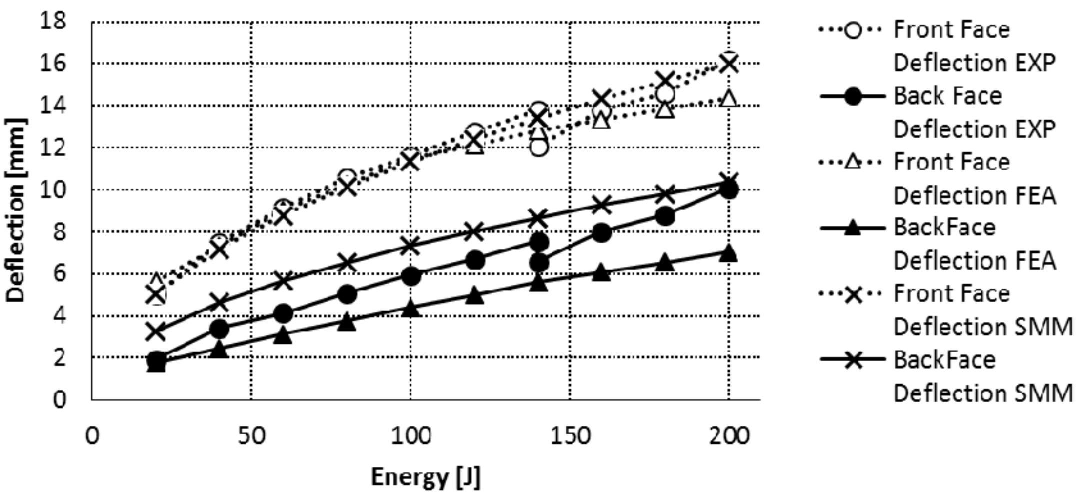

Figure 9. Front and back-face transverse deformations of sandwich panel during hard-body impact including experimental, FEA and analytical solutions.

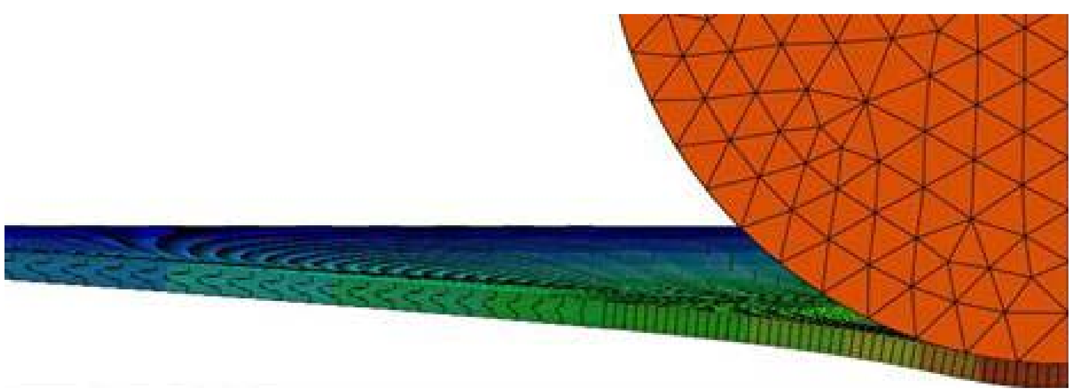

Figure 10. Local deformation of sandwich panel during hard-body impact.

6. Conclusions

Quasi-static and dynamic testing has been undertaken of material coupons and sandwich panel structures for a range of polymeric foam types. This includes through thickness compression and block shear coupons, four-point loaded sandwich beams and hard-body impact of sandwich panels. Implicit and Explicit FEA models have been developed for each loading case and used to investigate the accuracy of alternative foam constitutive models.

In the case of through thickness compression the testing identified significant local inhomogeneity of the materials, which affects their yield and plastic behavior. The ABAQUS Crushable Foam constitutive model simulated the compressive stress-strain behavior well, however the model did not accurately simulate tensile and shear behaviour in beams, limiting its applicability in more realistic loading scenarios such as a transversely loaded beams or panels.

In the case of the beam testing the Crushable Foam model matched the experimental data better than the Hyperfoam, Linear Elastic, and Linear Elastic Perfectly Plastic models. However it yielded at a lower flexural load and remained slightly stiffer during post yield behaviour than the experiment. It is also limited in its capabilities for large shear deformations because it does not accurately model tensile failure modes. The panel models demonstrated the complexity of the 3D stress and strain fields in these scenarios, including apparent through thickness compressions of more than 85% for hard-body impacts due to in-plane foam plastic deformations None of the currently available foam constitutive models were able to accurately capture all of the observed core deformations for this case.

Further work is needed to extend the capability of foam constitutive models, including better capturing the full 3D yield and plasticity behavior, and also including rate dependency.

Acknowledgments

The support of the USA Office of Naval Research through programme managers Dr. Yapa Rajapakse and Dr. Ramesh Kolar (Grant N62909-15-1-2067), and Tobias Mayr of BMW AG Munich are gratefully acknowledged.

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