OptumG3

Verification of shell element with rigid plastic properties

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1 Introduction

1.1 Shell element

OptumG3 uses a triangular shell element with a quadratic displacement field. The stress and moment fields are linear and described by a total of 18 variables. The in-plane part of the shell element contributes to 7 nodes, whereas one is a centre node and the remaining 6 are corner nodes and edge (midpoint) nodes. The plate part of the shell element uses the same corner and edge nodes as well as two nodes along each edge for moment continuity.

1.2 Upper, lower and mixed

Currently in OptumG3 the shell element is based on a so-called mixed formulation which in essence is a hybrid, or mixed, formulation of an upper and lower bound formulation. The output results when using the shell element with a mixed formulation is guaranteed to be within the brackets of the upper (unsafe) and lower (safe) bounds. The hybrid formulation ensures an superb precision.

Currently in OptumG3 the mixed formulation is the only element available.

1.3 Material models and yield conditions

Three shell models are available for the yield criterion, namely von Mises, Johansen, and Nielsen. General for all three models is that plate bending and in-plane actions are handled completely separate.

Von Mises

The von Mises model uses a criterion based on the second stress invariant, J_2, for the in-plane action,and an identical model with the moment variables for the plate bending. In principal stresses (and moments) the yield surface has the shape of an ellipse. In OptumG3, the user must supply a yield moment [kNm/m] for the plate bending, and a yield strength [MPa] as well as a sectional area [m^2/m] (equivalent to the thickness for planar shells). In general, the von Mises model is mostly suited for metals.

Johansen

In Johansen model, the first and second principal stresses and moments are independent, and the yield surface takes the shape of a box. For the in-plane action, a compressive strength [MPa], a tensile strength [MPa], and a sectional area [m^2/m] define the capacity. For plate bending, only a single yield moment [kNm/m] is needed. The Johansen model is suited for reinforced concrete shells with isotropic reinforcement.

Nielsen

The Nielsen model expands the Johansen model. For the in-plane action, the model uses a single tensile strength corresponding identical reinforcement in the x and y-directions. For plate bending, a total of four yield moments are required in order to define the yield envelope, namely positive and negative yield moments in the x and y-directions. The Nielsen model is suited for reinforced concrete shells with anisotropic reinforcement.

2 Square plate with fixed supports – isotropic Nielsen

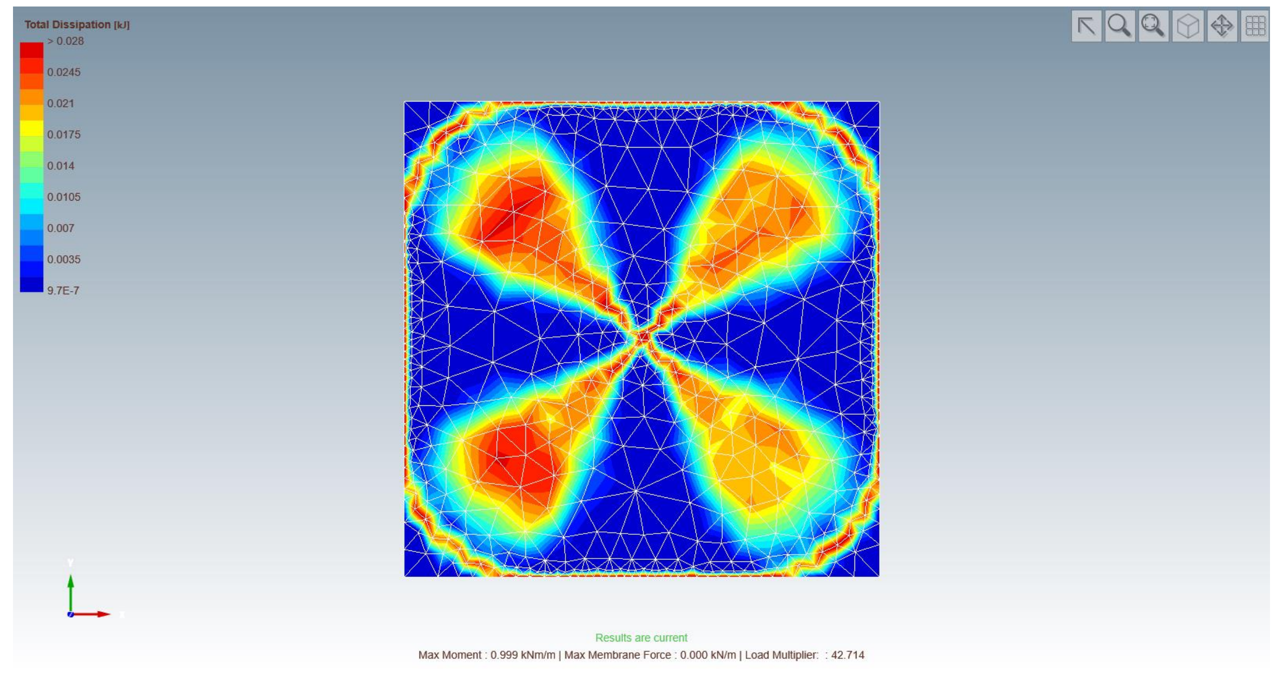

Figure **1: Square plate with fixed supports. Plastic dissipation displaying collapse mechanism**

Benchmark	42.71
Results	42.85
Discrepancy	0.33%

General description:
Square 1x1m isotropic reinforced concrete plate. All edges with fixed supports Loaded with unit area load of 1.0 kPa

Material properties:

Model Parameters	
Model	Rigid-Plastic
Yield Condition	Nielsen
Yield Moment x-pos, $m_{px}+$ (kNm/m)	1
Yield Moment x-neg, $m_{px}-$ (kNm/m)	1
Yield Moment y-pos, $m_{py}+$ (kNm/m)	1
Yield Moment y-neg, $m_{py}-$ (kNm/m)	1
Compressive Strength, f_c (MPa)	1
Tensile Strength, f_t (MPa)	1
Sectional Area, A (m^2/m)	0.01
Density, ρ (kg/m^3)	0

Partial factors:
Unity

Reference:
M.P. Nielsen, Limit Analysis and Concrete Plasticity, CRC Press (2011), p. 452

3 Hexagonal plate with simple supports. Isotropic Nielsen

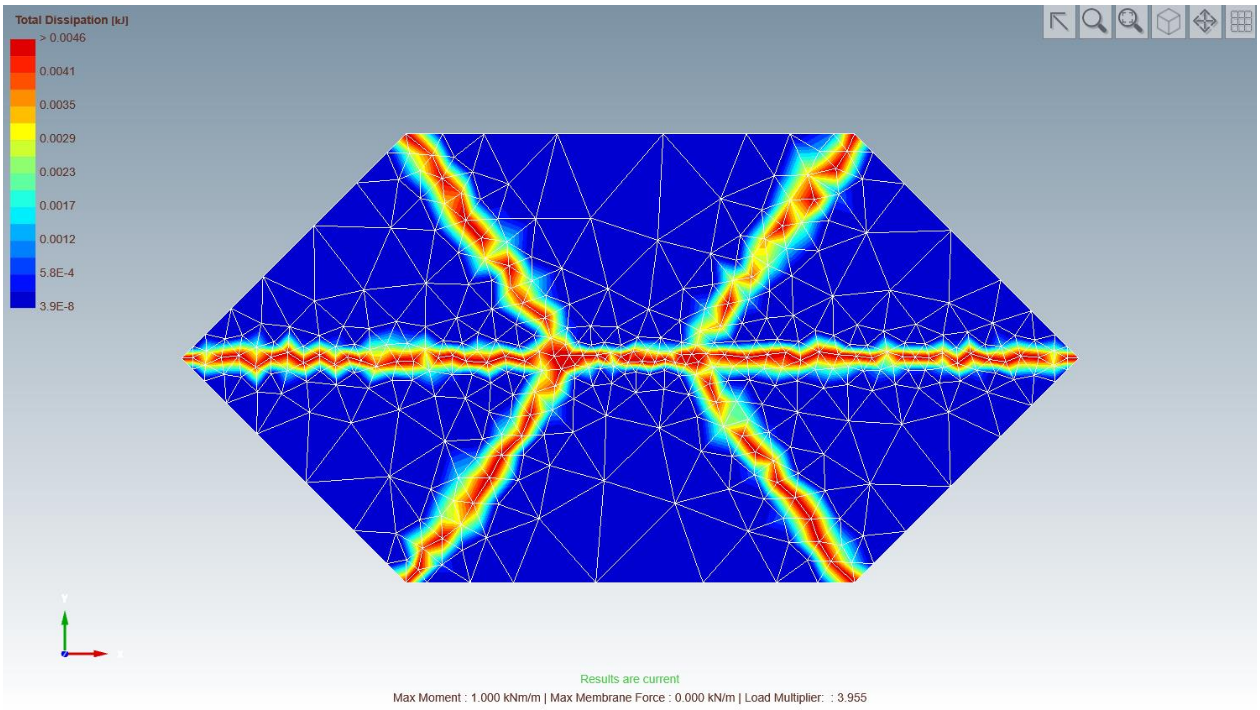

Figure **2: Hexagonal plate with simple supports. Plastic dissipation displaying collapse mechanism.**

Benchmark	3.956
Results	3.955
Discrepancy	0.03%

General description:
Hexagonal isotropic reinforced concrete plate. All edges with simple supports Loaded with unit area load of 1.0 kPa. Side lengths 2.0 m and 1.4142 m.

Material properties:

Model Parameters	
Model	Rigid-Plastic
Yield Condition	Nielsen
Yield Moment x-pos, m_{px+} (kNm/m)	1
Yield Moment x-neg, m_{px-} (kNm/m)	1
Yield Moment y-pos, m_{py+} (kNm/m)	1
Yield Moment y-neg, m_{py-} (kNm/m)	1
Compressive Strength, f_c (MPa)	1
Tensile Strength, f_t (MPa)	1
Sectional Area, A (m^2/m)	0.01
Density, ρ (kg/m^3)	0

Partial factors:
Unity

Reference:
M.P. Nielsen, Limit Analysis and Concrete Plasticity, CRC Press (2011), p. 450

4 Rectangular plate with simple supports. Isotropic Nielsen

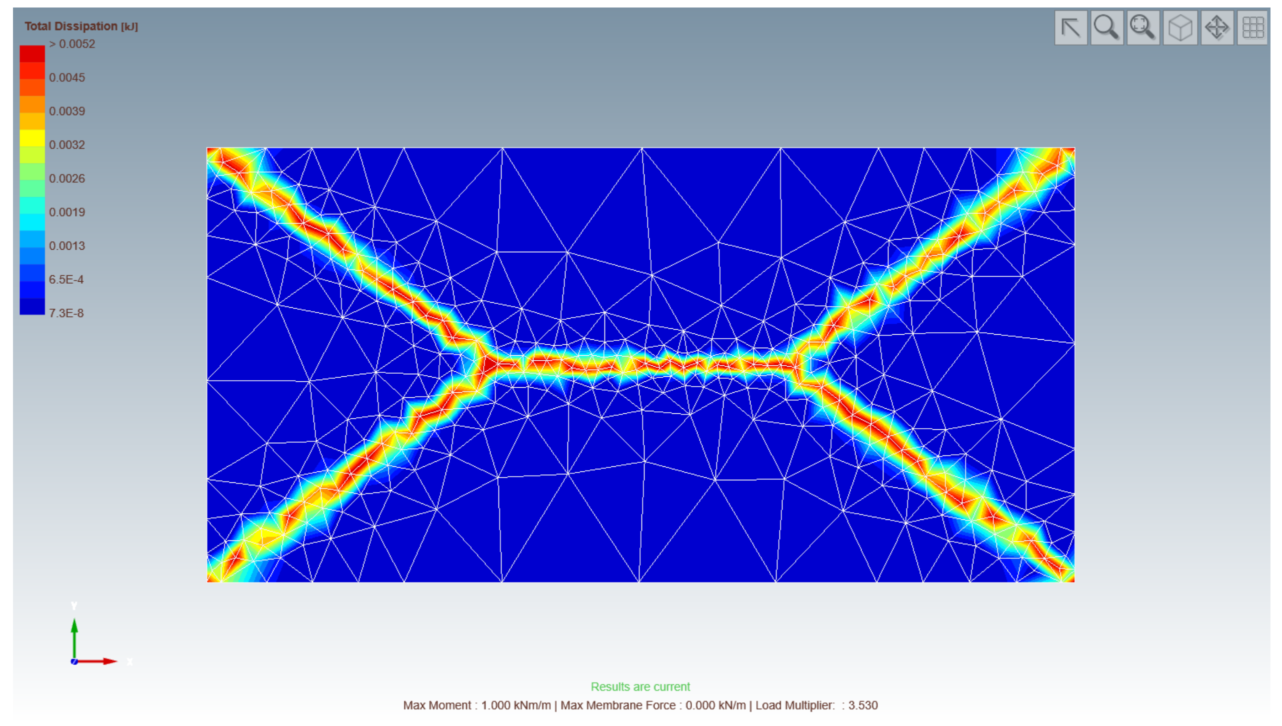

Figure **3: Rectangular plate with simple supports. Plastic dissipation displaying collapse mechanism**

Benchmark	3.535
Results	3.530
Discrepancy	0.14%

General description:
Rectangular 2x4 m isotropic reinforced concrete plate. All edges with simple supports Loaded with unit area load of 1.0 kPa.

Material properties:

Model Parameters	
Model	Rigid-Plastic
Yield Condition	Nielsen
Yield Moment x-pos, m_{px}+ (kNm/m)	1
Yield Moment x-neg, m_{px}- (kNm/m)	1
Yield Moment y-pos, m_{py}+ (kNm/m)	1
Yield Moment y-neg, m_{py}- (kNm/m)	1
Compressive Strength, f_c (MPa)	1
Tensile Strength, f_t (MPa)	1
Sectional Area, A (m^2/m)	0.01
Density, ρ (kg/m^3)	0

Partial factors:
Unity

Reference:
M.P. Nielsen, Limit Analysis and Concrete Plasticity, CRC Press (2011), p. 467