UNIVERSITY of Liège

GENERALIZED SHAPE OPTIMIZATION USING XFEM AND LEVEL SET METHODS

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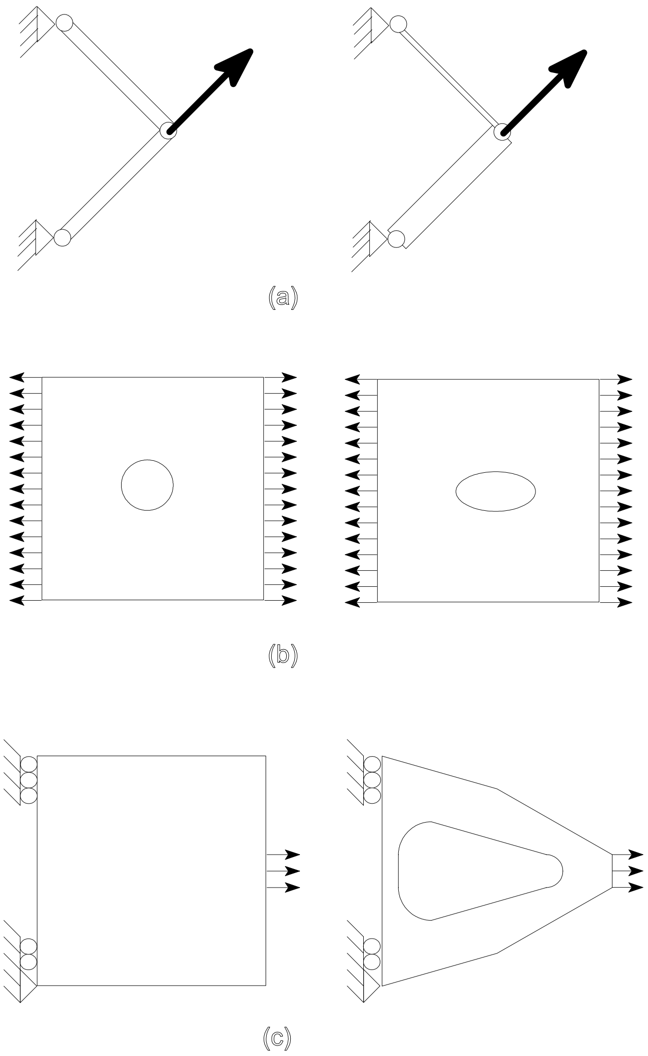
OUTLINE

- Introduction
- eXtended Finite Element Method (XFEM)
- Level Set Method
- Problem Formulation
- Sensitivity Analysis
- Applications
  - Implementation
  - Plate with a hole
- Conclusion

INTRODUCTION

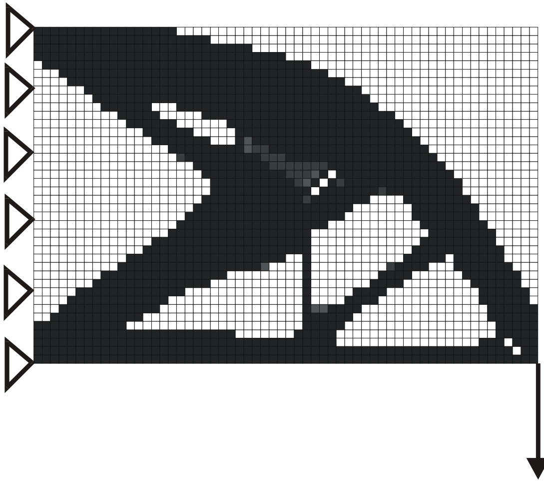
- Types of variables
  - (a) Sizing optimization
  - (b) shape optimization
  - (c) topology optimization
  - (d) material selection

- Types of problems
  - Structural
  - Multidisciplinary

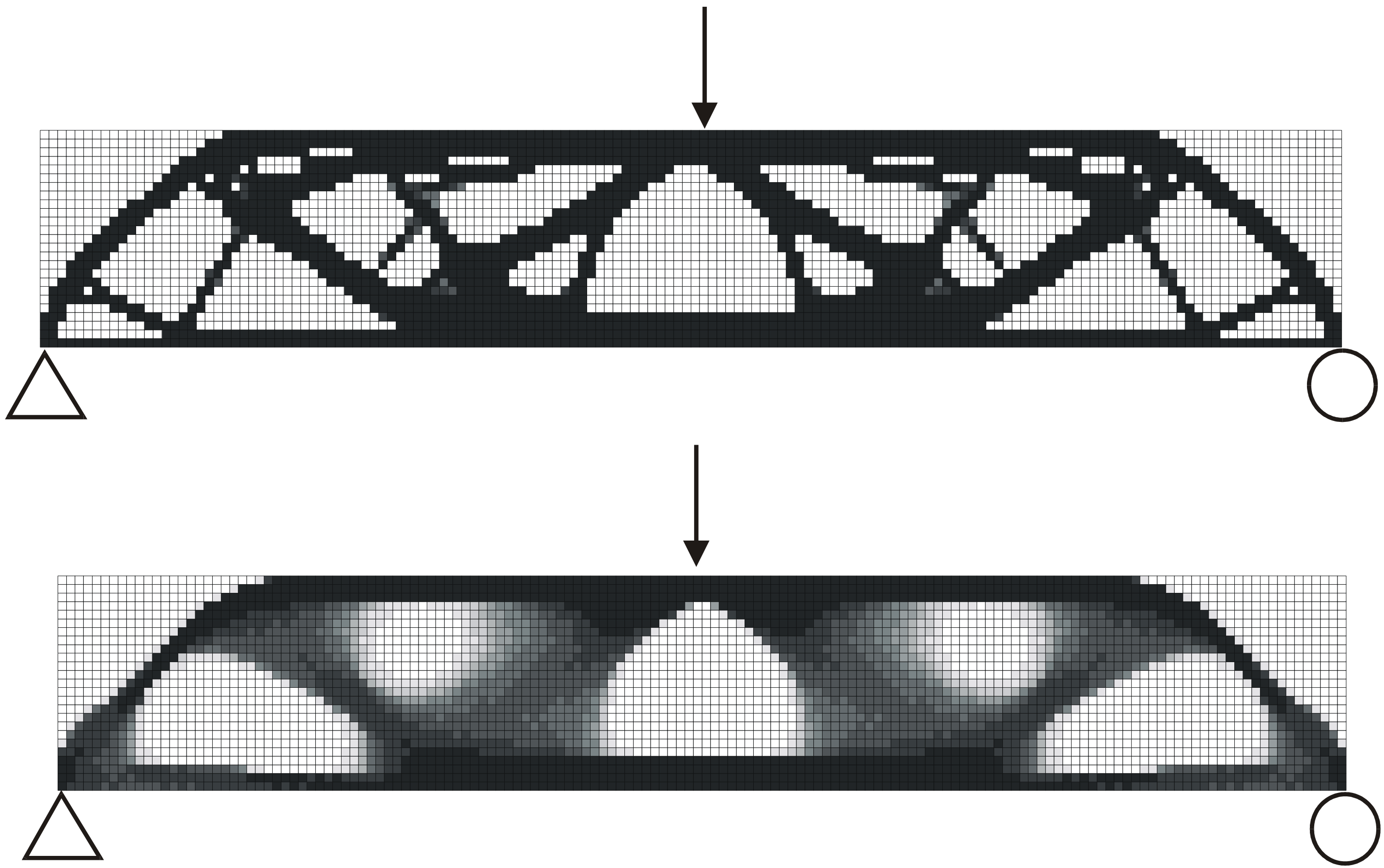


INTRODUCTION

- TOPOLOGY OPTIMIZATION (Bendsøe & Kikuchi, 1988)
  - Optimal material distribution
  - Optimal topology without any a priori
  - Fixed mesh
  - Design variables
    - = Local density parameters
    - Many thousands of design variables
  - Simple design problem:
    - Minimum compliance s.t. volume constraint
    - Local constraints are difficult to handle
    - Geometrical constraints (often manufacturing constraints) are difficult to define and to control
  - Preliminary design: interpretation phase necessary to come to a CAD model
  - Great industrial applications

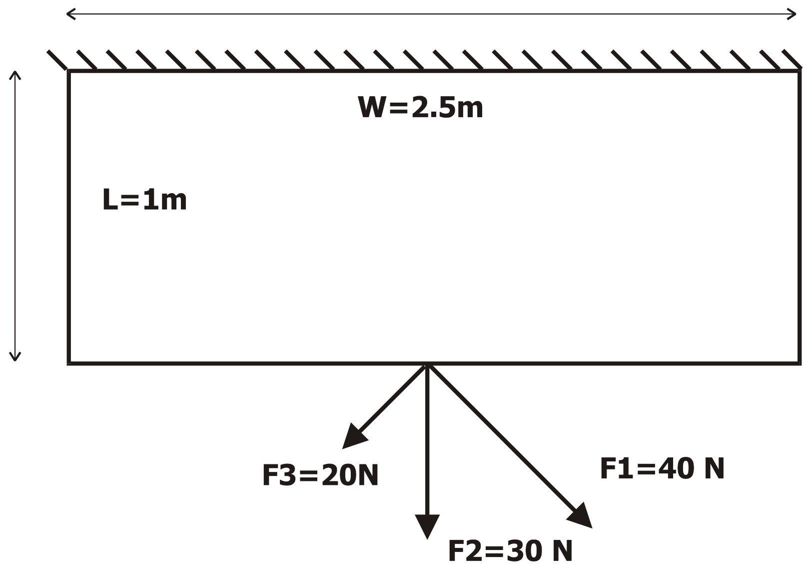


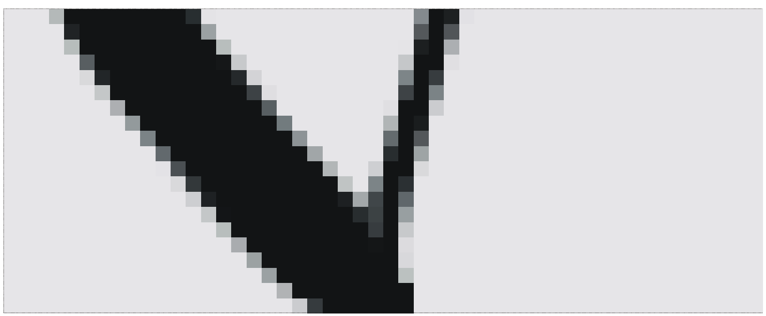
INTRODUCTION



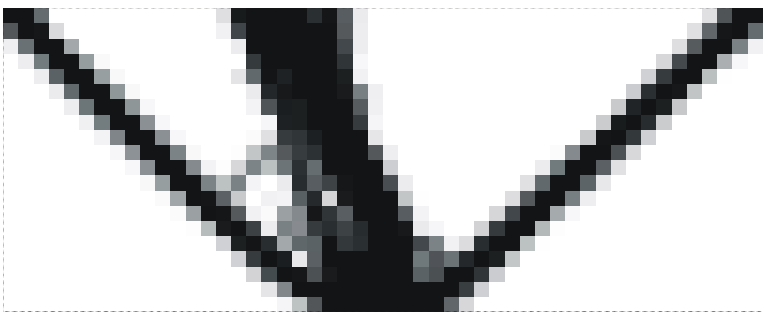
Perimeter constraint

INTRODUCTION





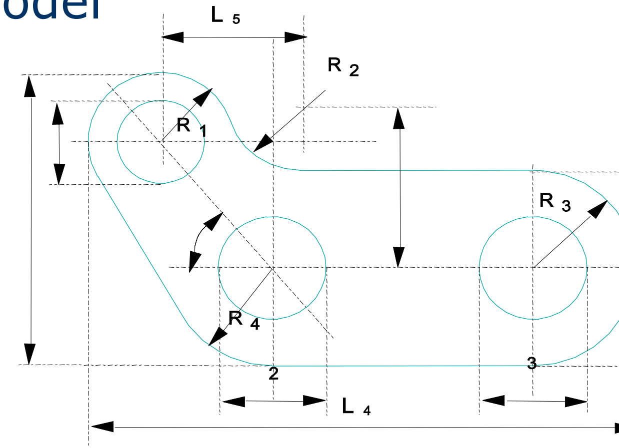
Min max compliance design



Min max stress design

INTRODUCTION

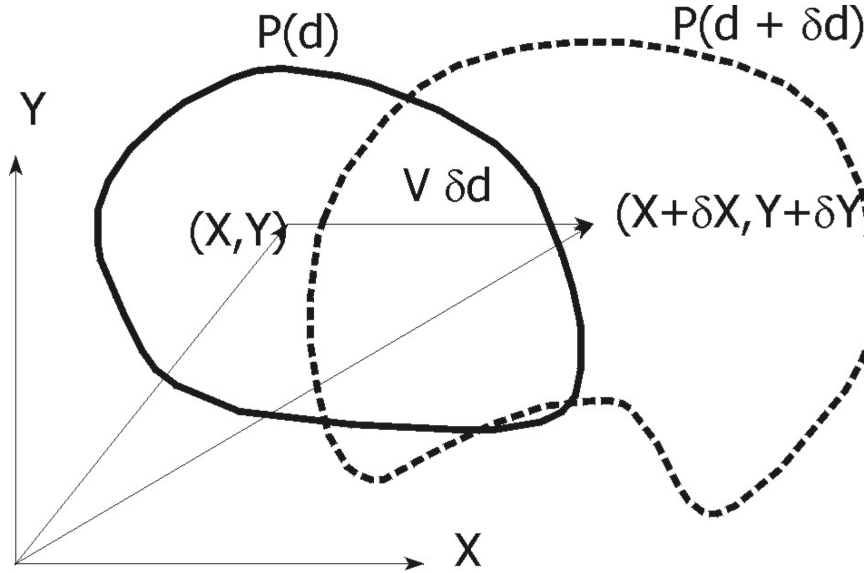
- SHAPE OPTIMIZATION
  - Modification of boundaries of CAD model
  - Fixed topology a priori
  - Design variables
    - = CAD model parameters
    - Small number of design variables
  - Quite complex design problems:
    - Large number of global and local constraints
    - Geometrical constraints easily included
  - Detailed design
  - Mesh management problems
    - Mesh modification / mesh distortion
    - Velocity field
  - Small number of industrial applications



INTRODUCTION

- Position of a point after a perturbation of the design variable d_i

$$X(d_i + \delta d_i) = X(d_i) + V_i \, \delta d_i$$
$$\text{with} \quad V_i = \partial X / \partial d_i$$

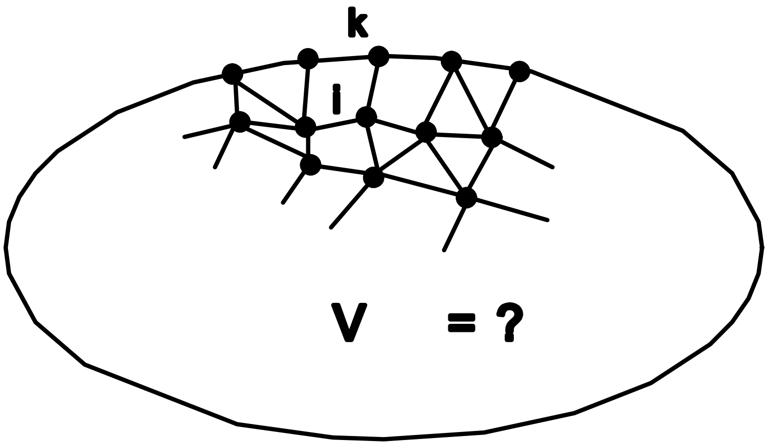


- Derivative of a response in a given point:

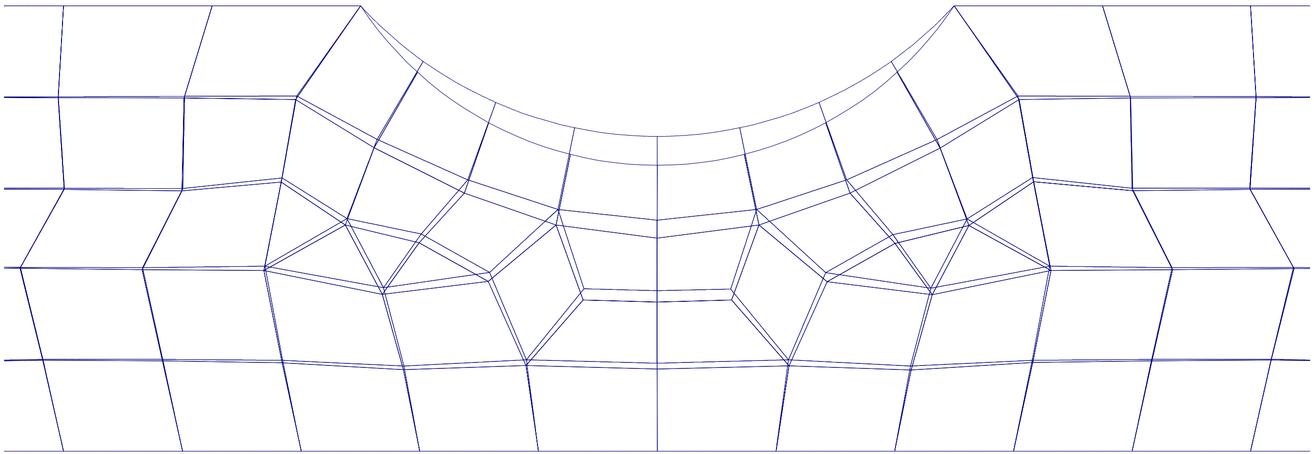
$$\frac{DR}{Dd_i} = \frac{\partial R}{\partial d_i} + \sum_k \frac{\partial R}{\partial X_k} \frac{\partial X_k}{\partial d_i}$$
$$= \frac{\partial R}{\partial d_i} + V_i \, \nabla R$$

Conclusion: determine the velocity field at first

INTRODUCTION



- Practical calculation of velocity field
  - Transfinite mapping
  - Natural / mechanical approach (Belegundu & Rajan, Zhang & Beckers)
  - Laplacian smoothing
  - Relocation schemes



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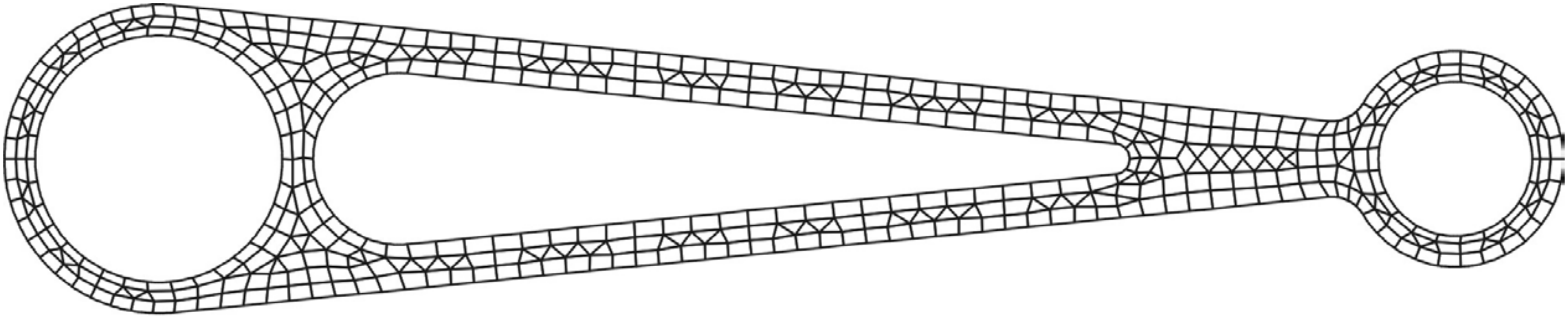
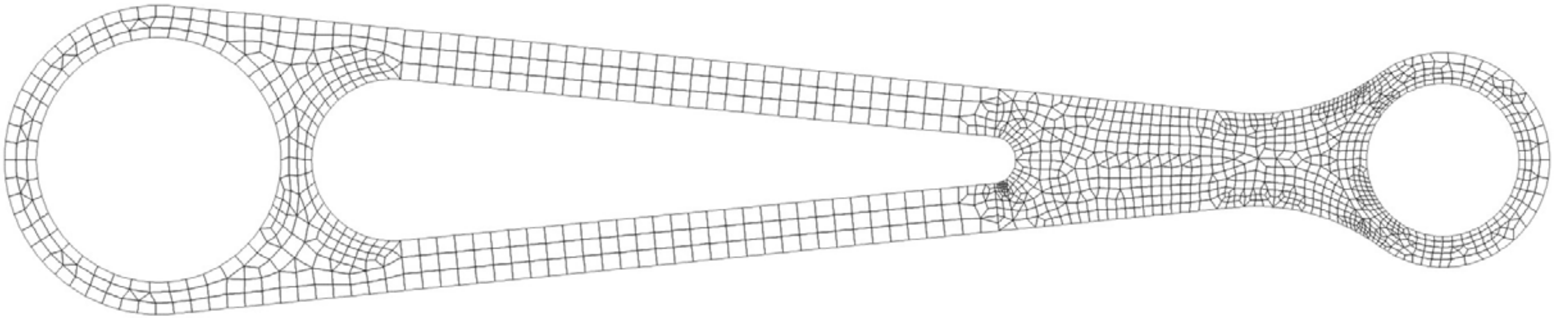


Without error control



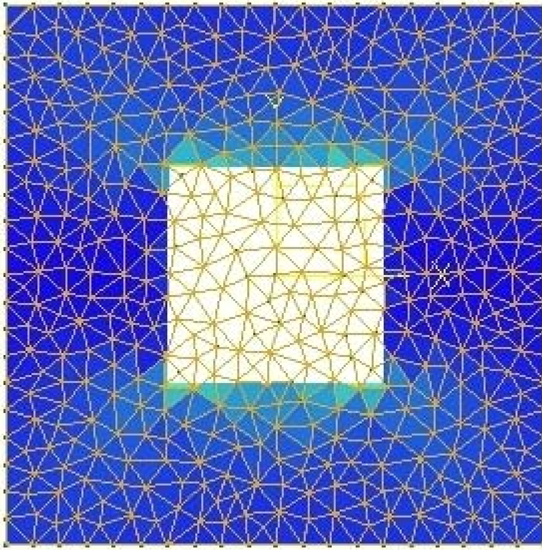
With error control

INTRODUCTION

- EXTENDED FINITE ELEMENT METHOD (XFEM)
  - alternative to remeshing methods
- LEVEL SET METHOD
  - alternative description to parametric description of curves
- XFEM + LEVEL SET METHODS
  - Efficient treatment of problem involving discontinuities and propagations
  - Early applications to crack problems. Moës et al. (1999)
  - Applications to topology optimisation Belytschko et al. (2003), Wang et al. (2003), Allaire et al. (2004)

INTRODUCTION

- THIS WORK
  - XFEM + Level Set methods = alternative method to shape optimisation
  - Intermediate approach between shape and topology optimisation
  - XFEM
    - work on fixed mesh
    - no mesh problems
  - Level Set
    - smooth curve description
    - modification of topology is possible
  - Problem formulation:
    - global and local constraints
    - small number of design variables



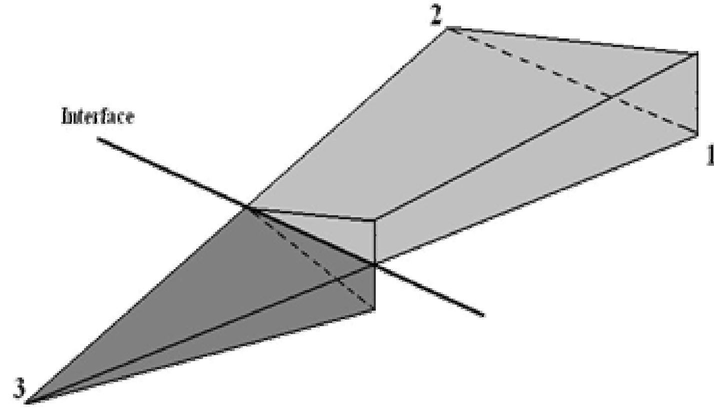
EXTENDED FINITE ELEMENT METHOD

- Early motivation : study of propagating crack in mechanical structures → avoid the remeshing procedure

- Principle :
  - Allow the model to handle discontinuities that are non conforming with the mesh
  - Add internal degree of freedom a_i
  - Add special shape functions $H(x)N_i(x)$ (discontinuous)

$$u = \sum_{i \in I} u_i \, N_i(x) + \sum_{i \in L} u_i \, N_i(x) \, H(x)$$

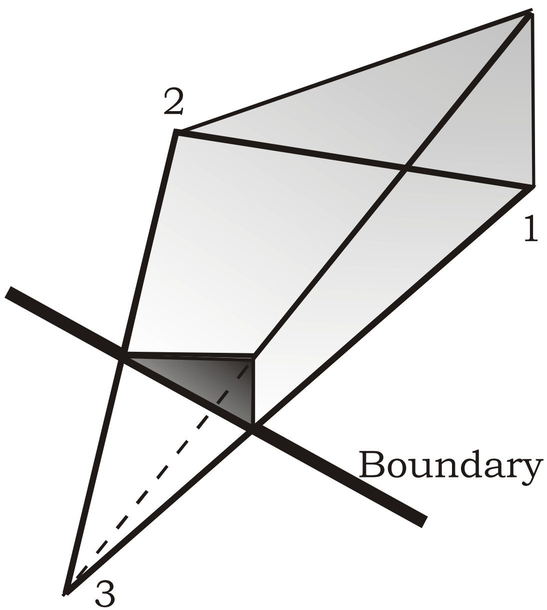
$$Kq = g \quad \Leftrightarrow \quad \begin{bmatrix} K_{uu} & K_{ua} \\ K_{au} & K_{aa} \end{bmatrix} \begin{bmatrix} u \\ a \end{bmatrix} = \begin{bmatrix} f_u \\ f_a \end{bmatrix}$$

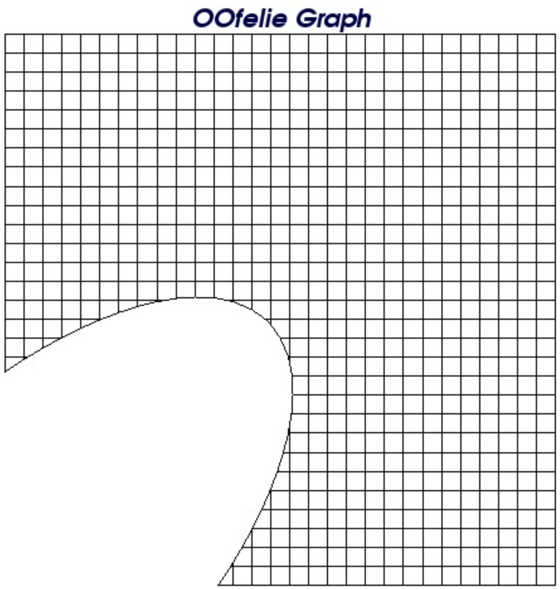


EXTENDED FINITE ELEMENT METHOD

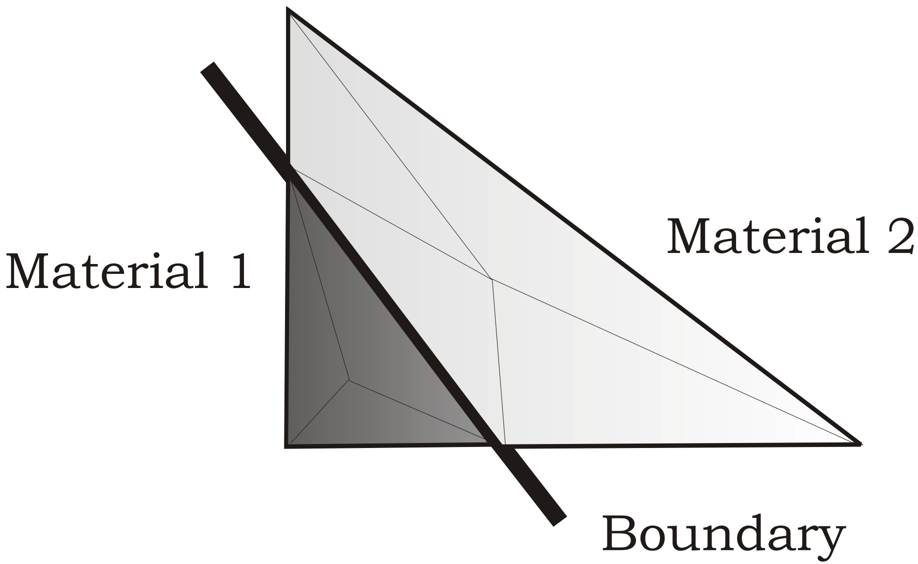
- Representing holes or material – void interfaces
  - Remove empty elements
  - Keep partially filled elements
  - Use XFEM numerical integration

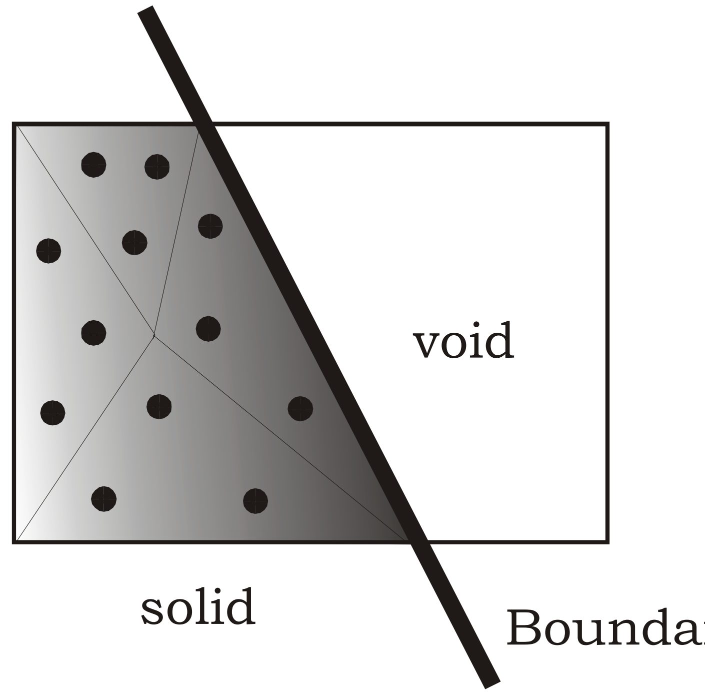
$$u = \sum_{i \in I} N_i(x)\, V(x)\, u_i \qquad V(x) = \begin{cases} 1 & \text{if node} \in \text{solid} \\ 0 & \text{if node} \in \text{void} \end{cases}$$





- Quadrangles and triangles XFEM elements
- Numerical integration
  - Division into sub-triangles
  - Integration over sub-triangles
  - Gauss points

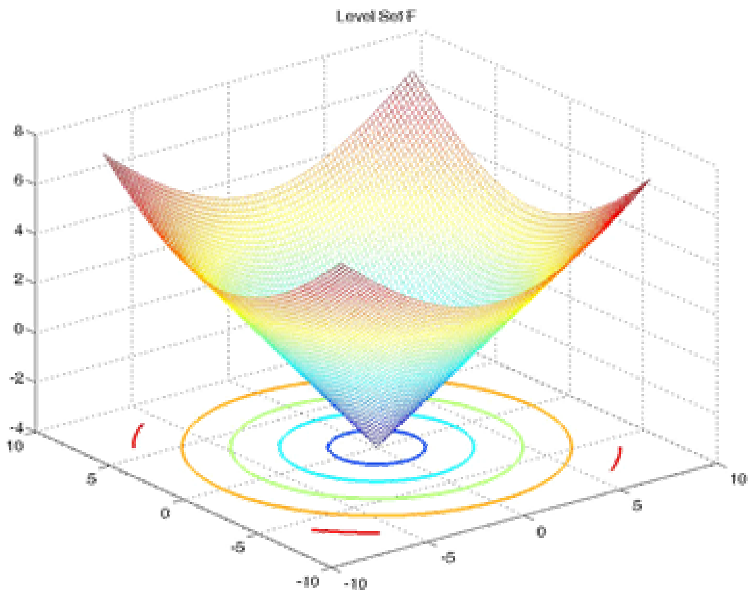




THE LEVEL SET METHOD

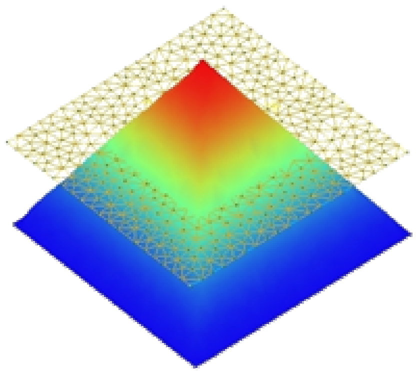
- Principle (Sethian, 1999)
  - Introduce a higher dimension
  - Implicit representation
  - Interface = the zero level of a function $\psi(x,t)=0$
- Possible practical implementation:
  - Approximated on a fixed mesh by the signed distance function to curve Γ:

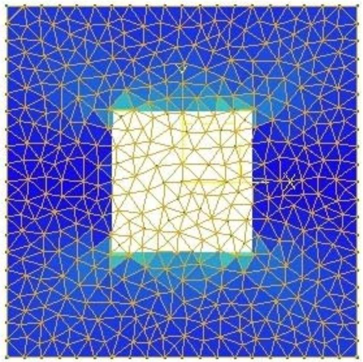
$$\psi(x,t) = \pm \min_{x_\Gamma \in \Gamma(t)} \left\| x - x_\Gamma \right\|$$



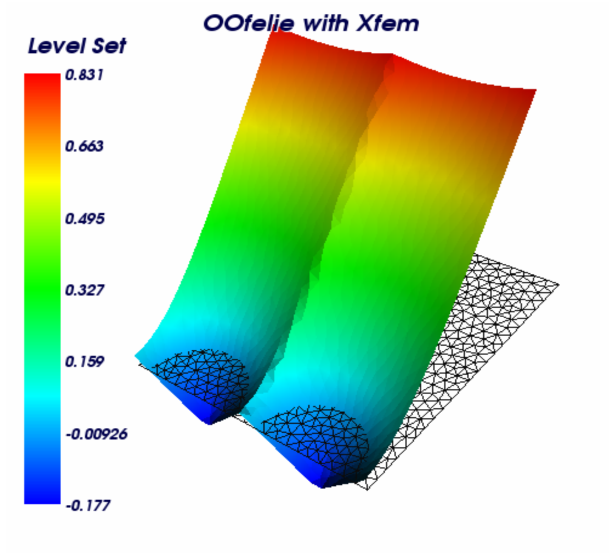
- Advantages:
  - 2D / 3D
  - Combination of entities: e.g. min / max

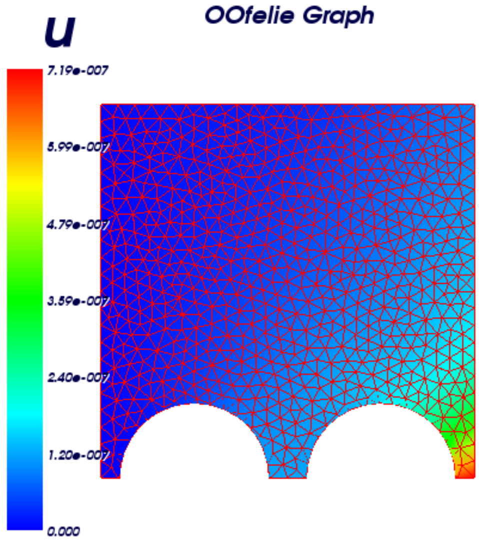
- Level Set of a square hole





- Combination of two holes





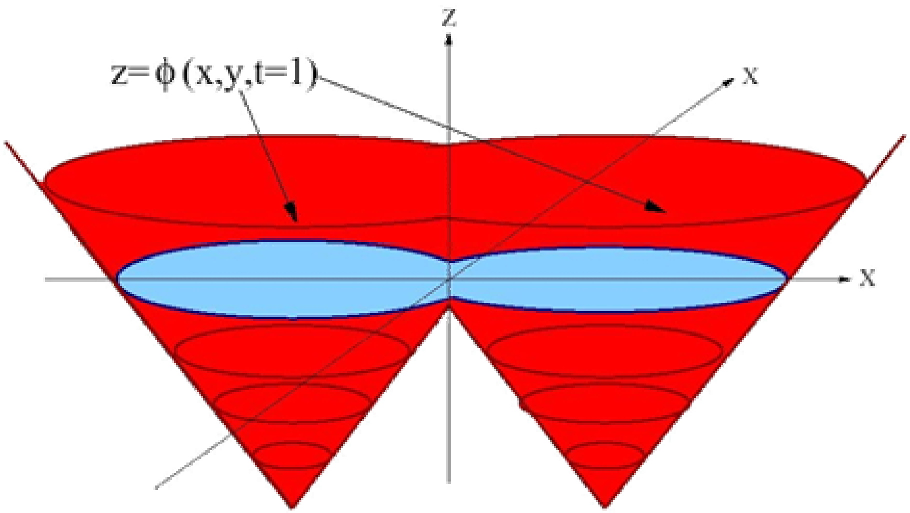
THE LEVEL SET METHOD

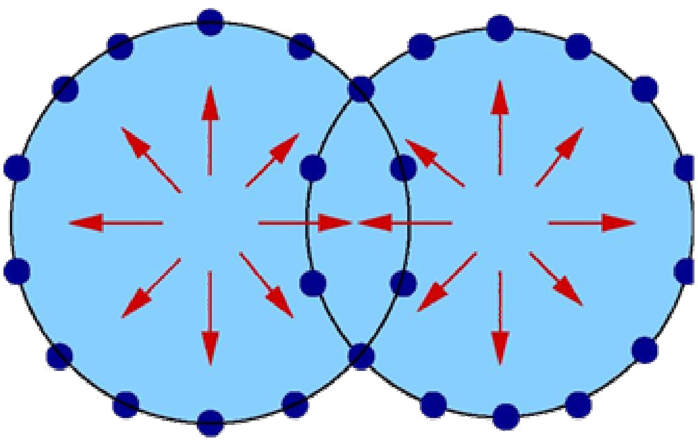
- Evolution of interface

$$\frac{\partial \psi}{\partial t} + V \left\| \nabla \psi \right\| = 0$$

$$\psi(x,t) = 0 \qquad \text{given}$$

  - V: velcocity function of Γ in the outward normal direction to interface





THE LEVEL SET METHOD

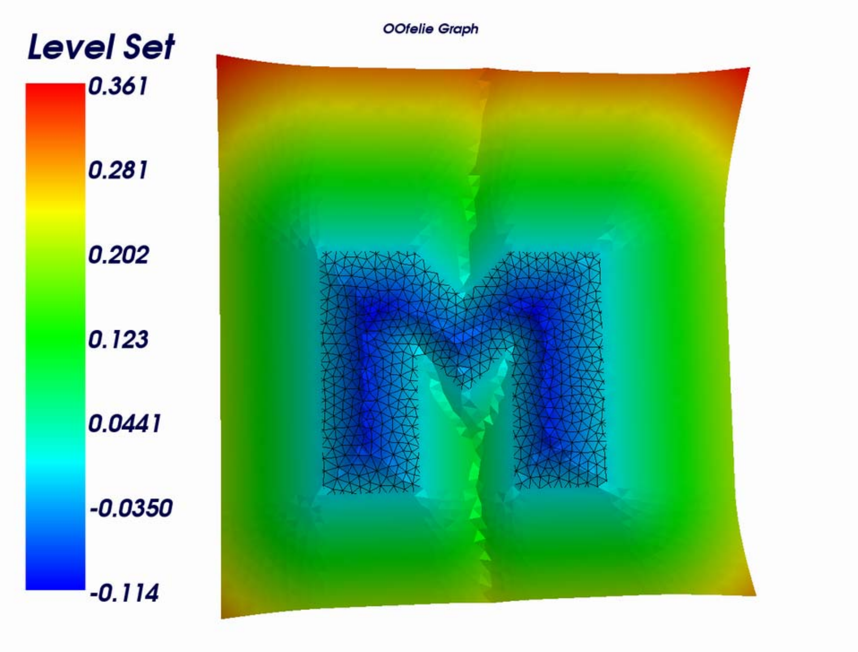
- In XFEM framework,
  - Each node has a Level Set dof
  - Interpolation using classical shape functions

$$\psi(x,t) = \sum_i \psi_i \; N_i(x)$$

  - Material assigned to a part of the Level Set (positive or negative)

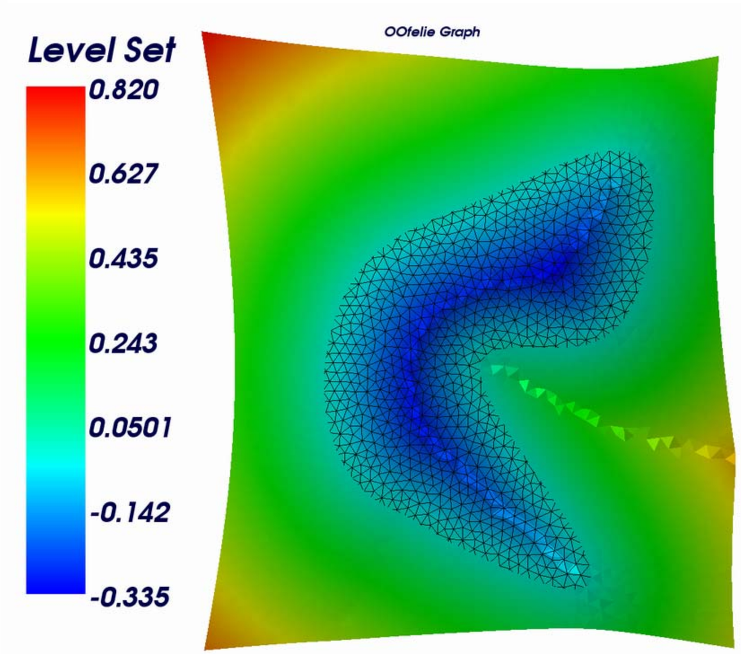
- Building a library of graphic primitives and features
  - Lines
  - Circles, ellipses, rectangles, triangles
  - NURBS
  - …

THE LEVEL SET METHOD



Level set defined by a set of points

Level set associated to a NURBS



PROBLEM FORMULATION

- Geometry description and material layout :
  - Using Level Sets
  - Basic Level Set features: circles, ellipses, rectangles, etc.
- Design Problem
  - Find the best shape to minimize a given objective functions while satisfying design constraints
- Design variables:
  - Parameters of Level Sets
- Objective and constraints
  - Mechanical responses: global (compliance) or local (displacement, stress)
  - Geometrical characteristics: volume, distance
- Problem formulation similar to shape optimization but simplified thanks to XFEM and Level Set!

PROBLEM FORMULATION

BECAUSE OF XFEM AND LEVEL SET

- The mesh has not to coincide with the geometry
- Work on a fixed mesh

- Sensitivity analysis: no velocity field and no mesh perturbation required

- Topology can be altered as entities can be merged or separated → generalized shape
- Introduction of new holes requires a topological derivatives

- Topology optimization can be simulated using a design universe of holes and an optimal selection problem (Missoum et al. 2000)

SENSITIVITY ANALYSIS

- Classical approach for sensitivity analysis in industrial codes: semi analytical approach

- Discretized equilibrium

$$\mathbf{K}\,\mathbf{u} = \mathbf{f}$$

- Derivatives of displacement

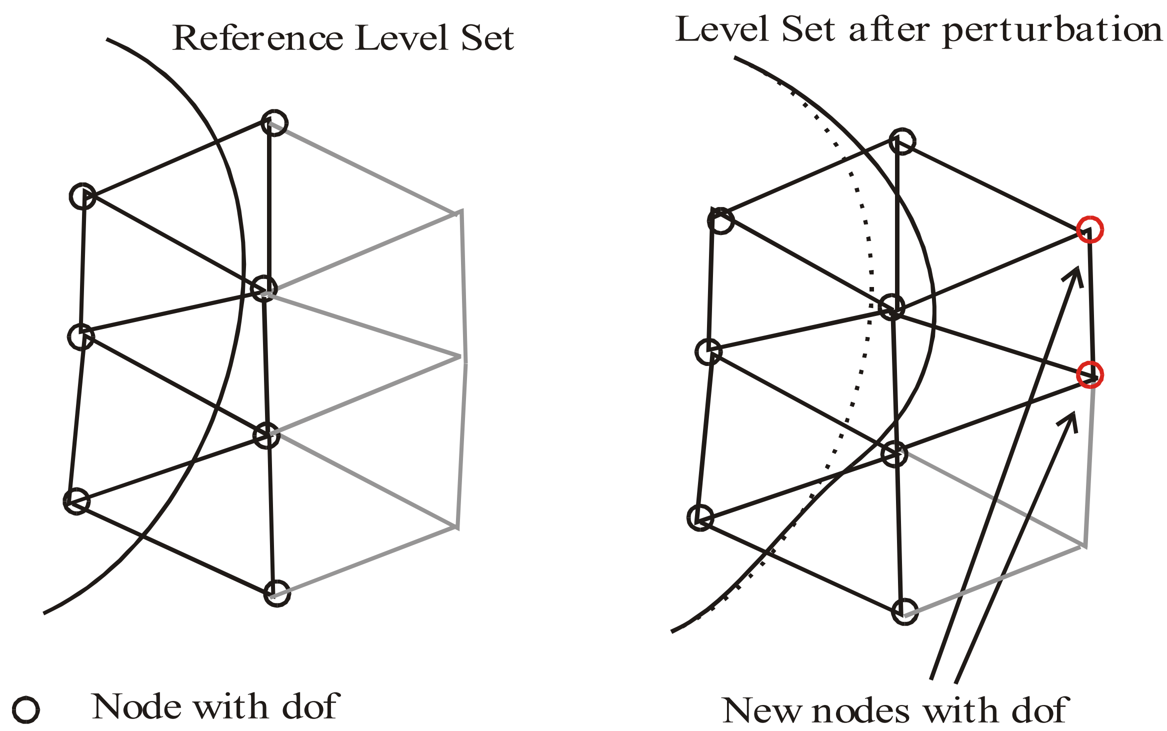
$$\mathbf{K}\,\frac{\partial \mathbf{u}}{\partial x} = \left(\frac{\partial \mathbf{f}}{\partial x} - \frac{\partial \mathbf{K}}{\partial x}\mathbf{u} \right)$$

- Semi analytical approach

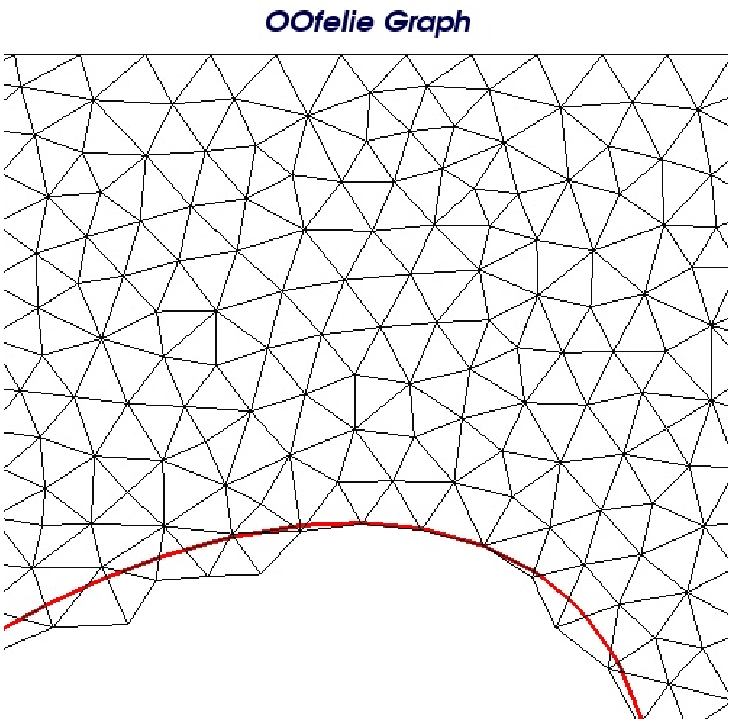
$$\frac{\partial \mathbf{K}}{\partial x} \approx \frac{\mathbf{K}(x+\delta x) - \mathbf{K}(x)}{\delta x} \qquad \frac{\partial \mathbf{f}}{\partial x} \approx \frac{\mathbf{f}(x+\delta x) - \mathbf{f}(x)}{\delta x}$$

SENSITIVITY ANALYSIS

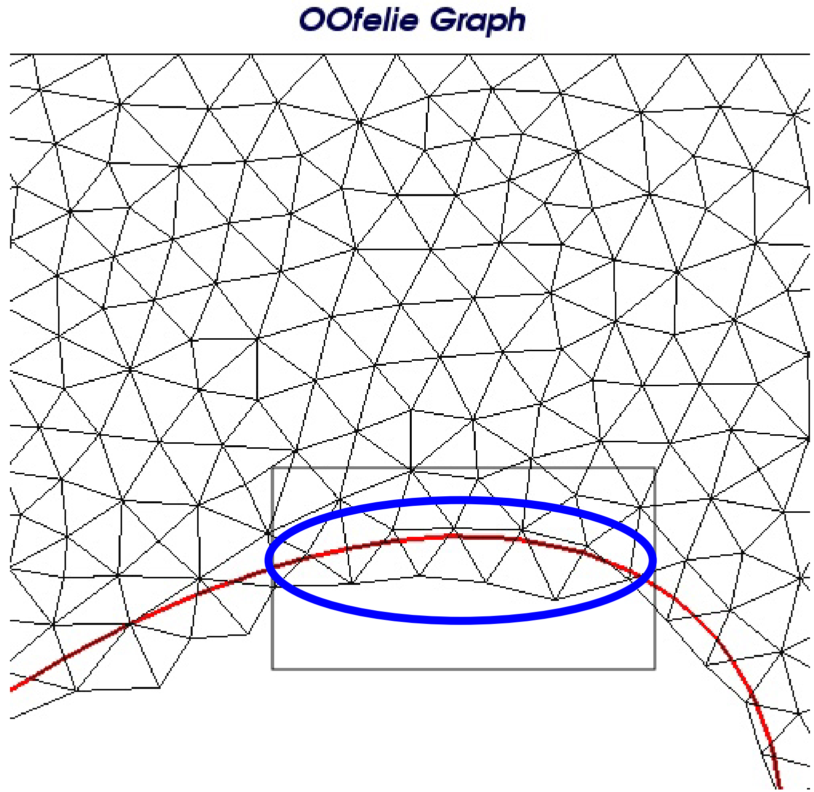
- Fixed mesh → no mesh perturbation
- However finite differences of stiffness matrix have to be made with a frozen number of dof
- Critical situations happen when some empty elements become partly filled with solid after perturbating of the level set :



SENSITIVITY ANALYSIS



Reference configuration



After level set perturbation

SENSITIVITY ANALYSIS

- Strategies to freeze the number of dof
  - analytical derivatives of stiffness matrix:
    - not general!
  - boundary layer in which all elements are retained
    - rigid modes, larger size of the problem
  - boundary layer with softening material (SIMP law)
    - lost of void / solid approximation
  - ignore the new elements that become solid or partly solid
    - small errors, but minor contributions
    - practically, no problem observed
    - efficiency and simplicity
    - validated on benchmarks

SENSITIVITY ANALYSIS

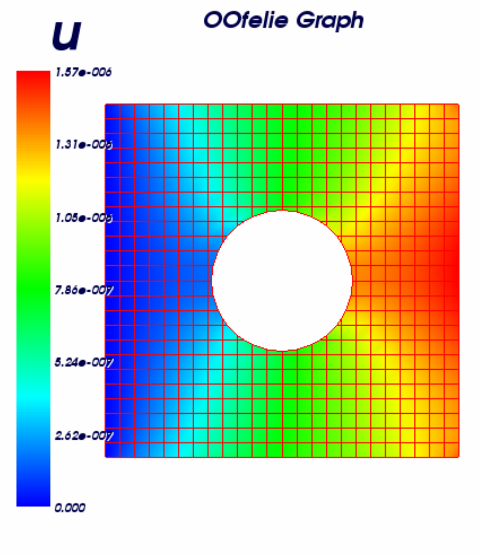
- Summary of the semi-analytical approach strategy

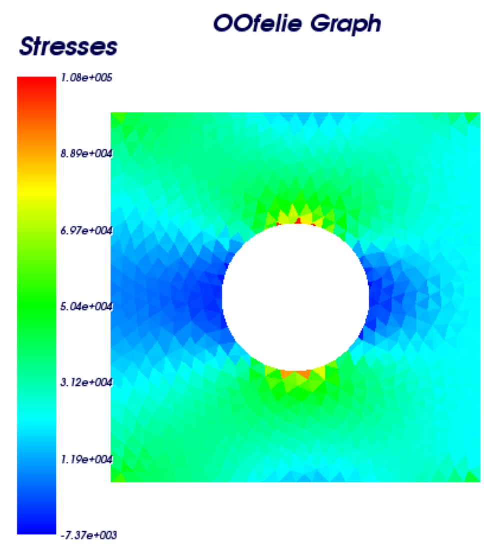
$$\frac{\partial \mathbf{K}}{\partial x} \approx \frac{\mathbf{K}(x+\delta x)-\mathbf{K}(x)}{\delta x}$$

Element initially	→ Solid	→ Cut	→ Void
Solid		OK	OK
Cut	OK	OK	OK
Void	Ignored	Ignored	

IMPLEMENTATION

- Preliminary investigations by coupling a standard XFEM code by Moës with a general open optimisation code (Boss Quattro)
- New implementation in a multiphysic finite element code in C++ (OOFELIE from Open Engineering www.open-engineering.com)
- XFEM library: 2D problems with a library of quadrangles and triangles.
- Available results for optimization:
  - Compliance
  - Displacements
  - Strains, Stresses
  - Energy per element
- Visualization:
  - Level Sets
  - Results





CONLIN OPTIMIZATION SOLVER

Direct solution of the original optimisation problem which is generally non-linear, implicit in the design variables

Minimise f(x)

s. t.: $g_j(x) \leq g_j^{max}$ j=1,m

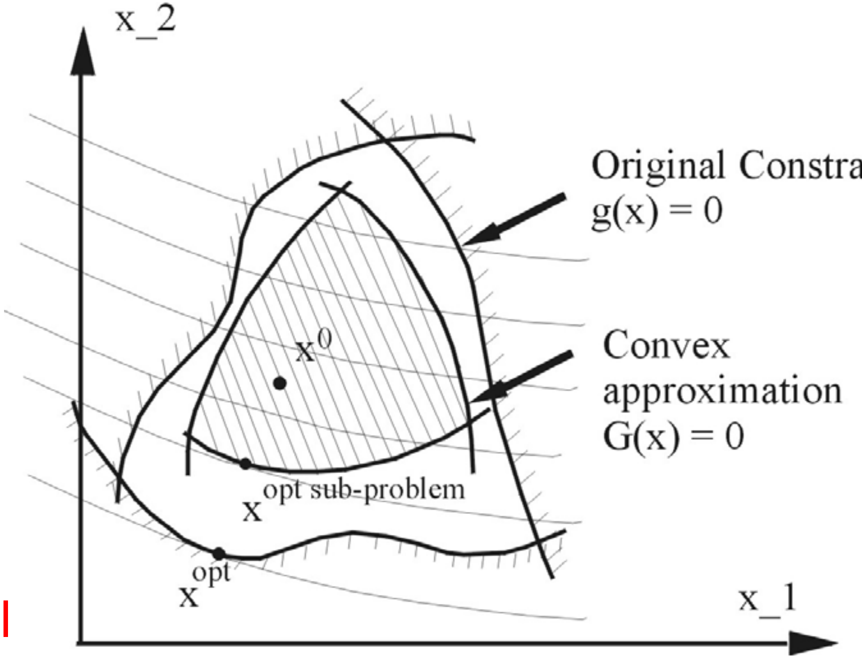
is replaced by a sequence of optimisation sub-problems

Minimise F(x)

s. t.: $G_j(x) \leq G_j^{max}$ j=1,m

by using approximations of the responses and using powerful mathematical programming algorithms

(Lagrangian duality methods or Quadratic Programming)



CONLIN OPTIMIZATION SOLVER

- FORTRAN computer programme

  can be used as a standalone software or an optimizer in open optimization tools
- General solver for structural and multidisciplinary problems: Sizing, shape, and topology problems
- Robust and Efficient
- Large scale problems:
  - 100.000 design variables (topology)
  - 5.000 constraints (shape)
  - 5.000 constraints and 5.000 design variables (topology)
- Implemented in several industrial optimisation tools: BOSS-Quattro, MBB-Lagrange, OptiStruct (Altair)

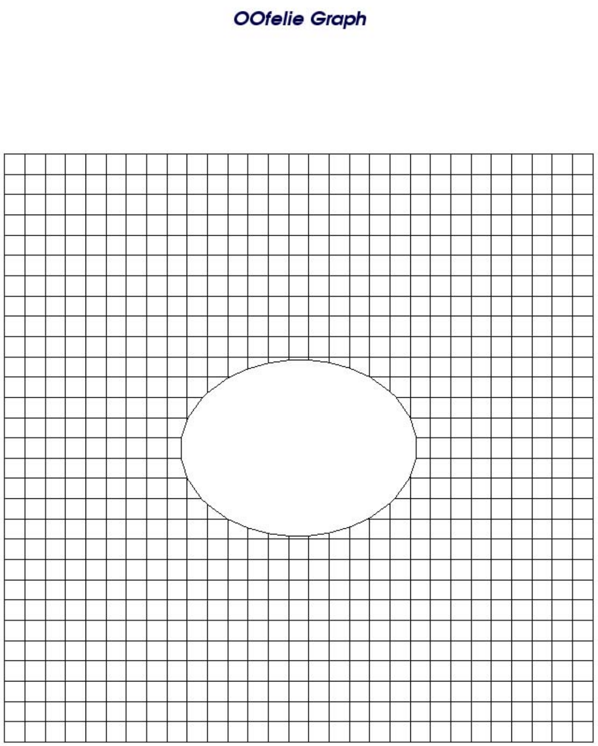
APPLICATIONS

CLASSICAL PROBLEM OF PLATE WITH A HOLE REVISITED

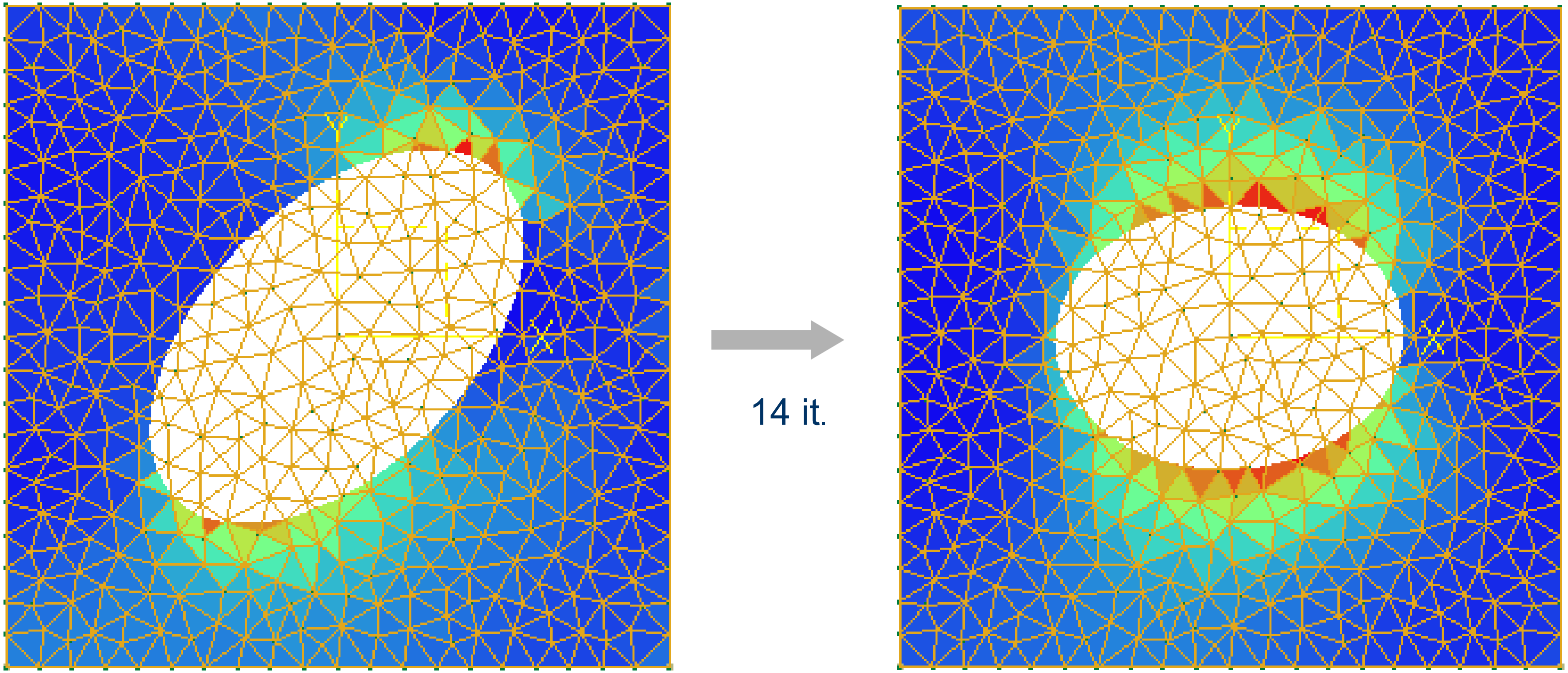
- Square plate with a hole
- Bidirectional stress field
- $\sigma_x = 2\ \sigma_0 \qquad \sigma_y = \sigma_0$
- E= 1 N/m², ν=0.3

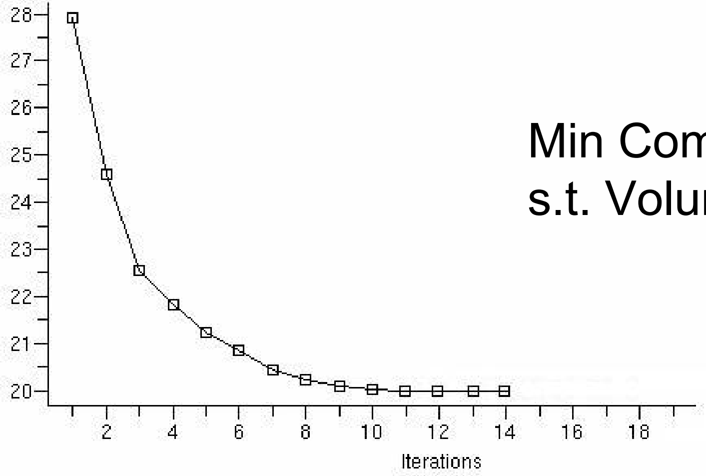
- Minimize compliance
  - st volume constraint
- Design variables: major axis a and orientation θ

- Mesh 30 x 30 nodes



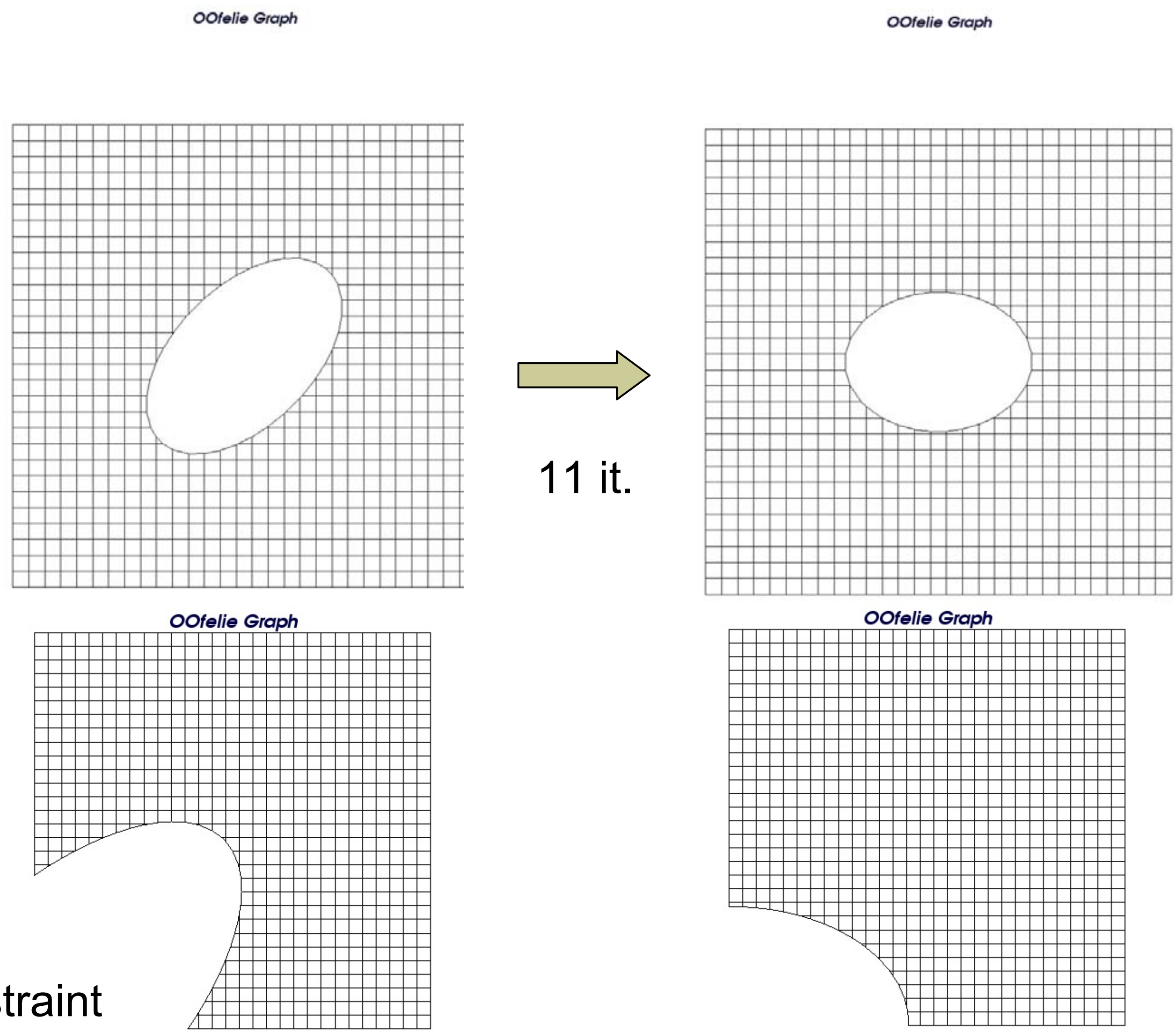
APPLICATIONS





Min Compliance
s.t. Volume constraint

APPLICATIONS



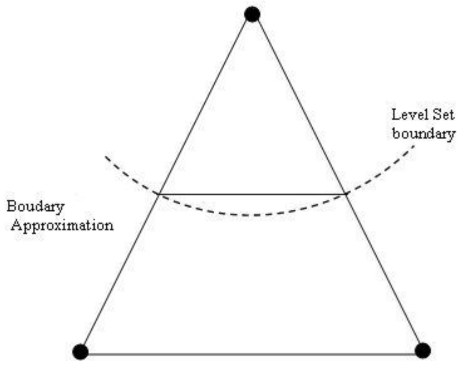
Min Compliance
s.t. Volume constraint

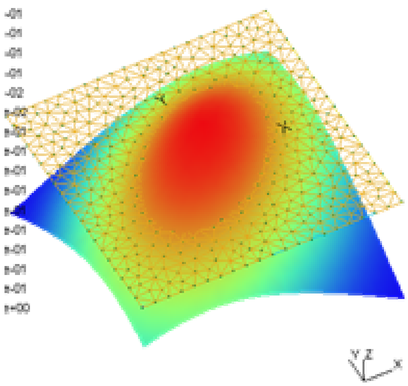
APPLICATIONS

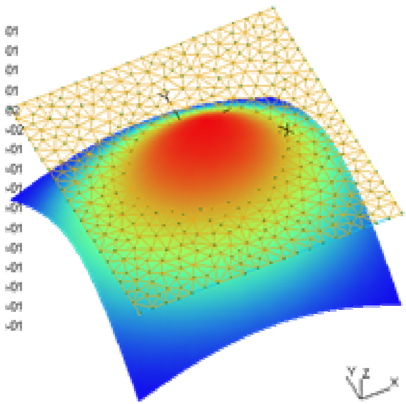
- Discretization error of the geometry using approx of level set
  Over-estimating geometric values :

		Xfem Iteration 1	*Xfem* Iteration 11	*Fem* Iteration 1	*Fem* Iteration 9
Objective function	Minimise U	27.9	20.2	26	18.3
Constraint	Surface < 3.45	3.59	3.45	3.50	3.45
Variable	1e-4$< \theta <$ 90	45	1e-4	45	0
Variable	1e-4<a< 1	0.5	1.06	0.5	0.88

- Representating interfaces inside an element :

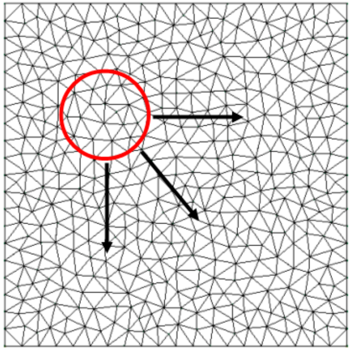


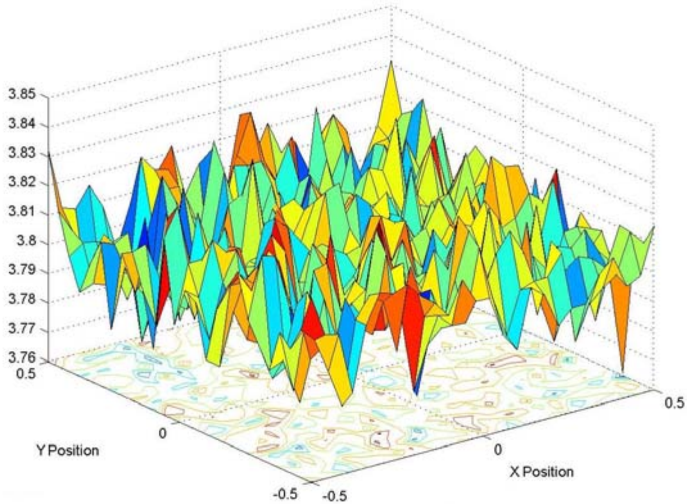




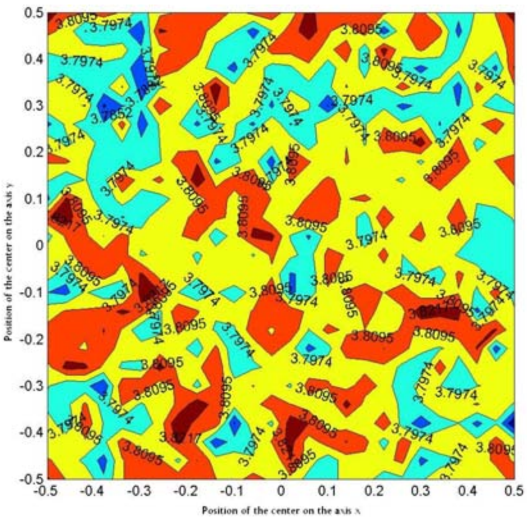
APPLICATIONS

- Linear interpolation of the Level Set may introduce discontinuity :
  - Parametric study of the surface of the plate
  - Variation of 1%

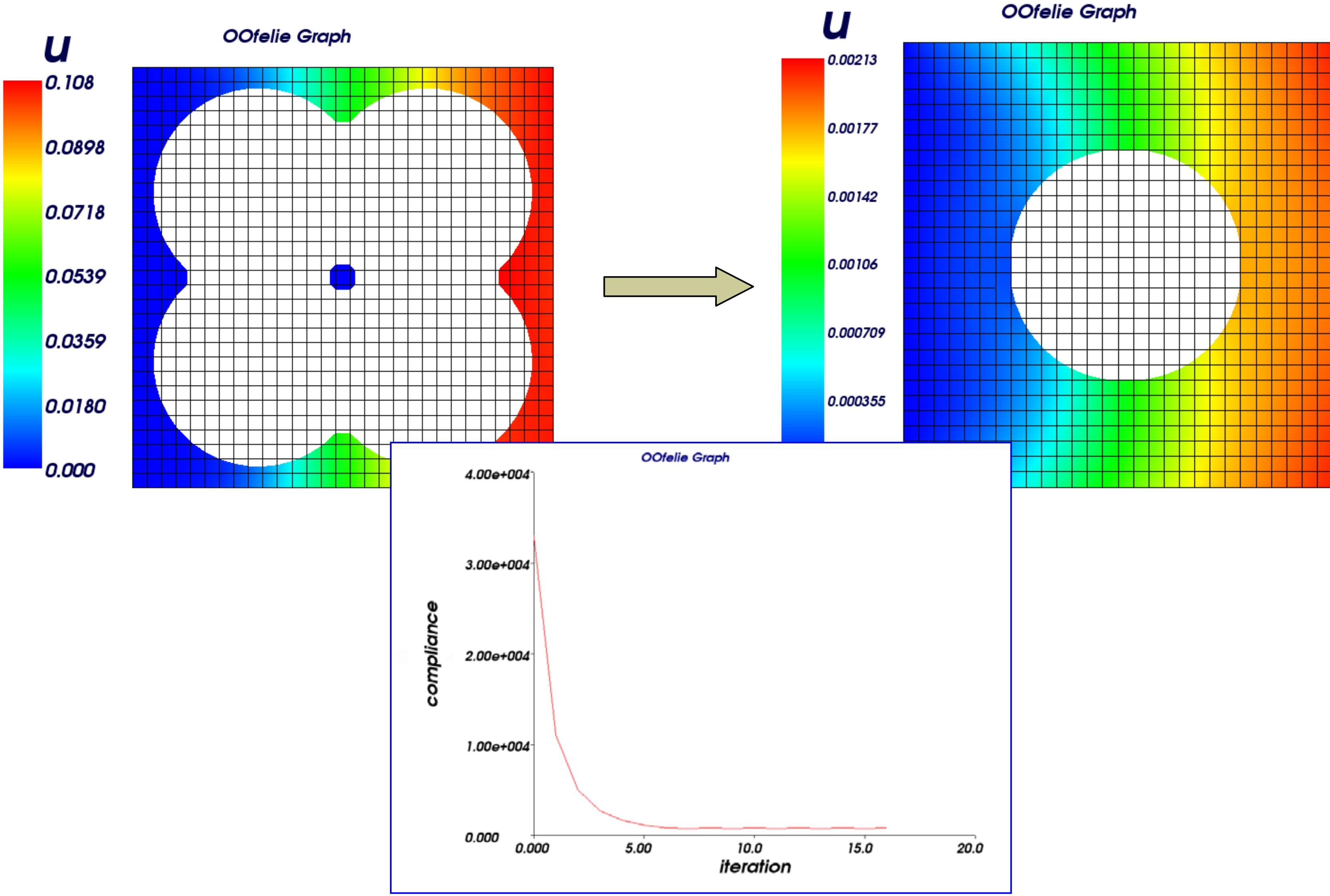




- Take care of numerical noise

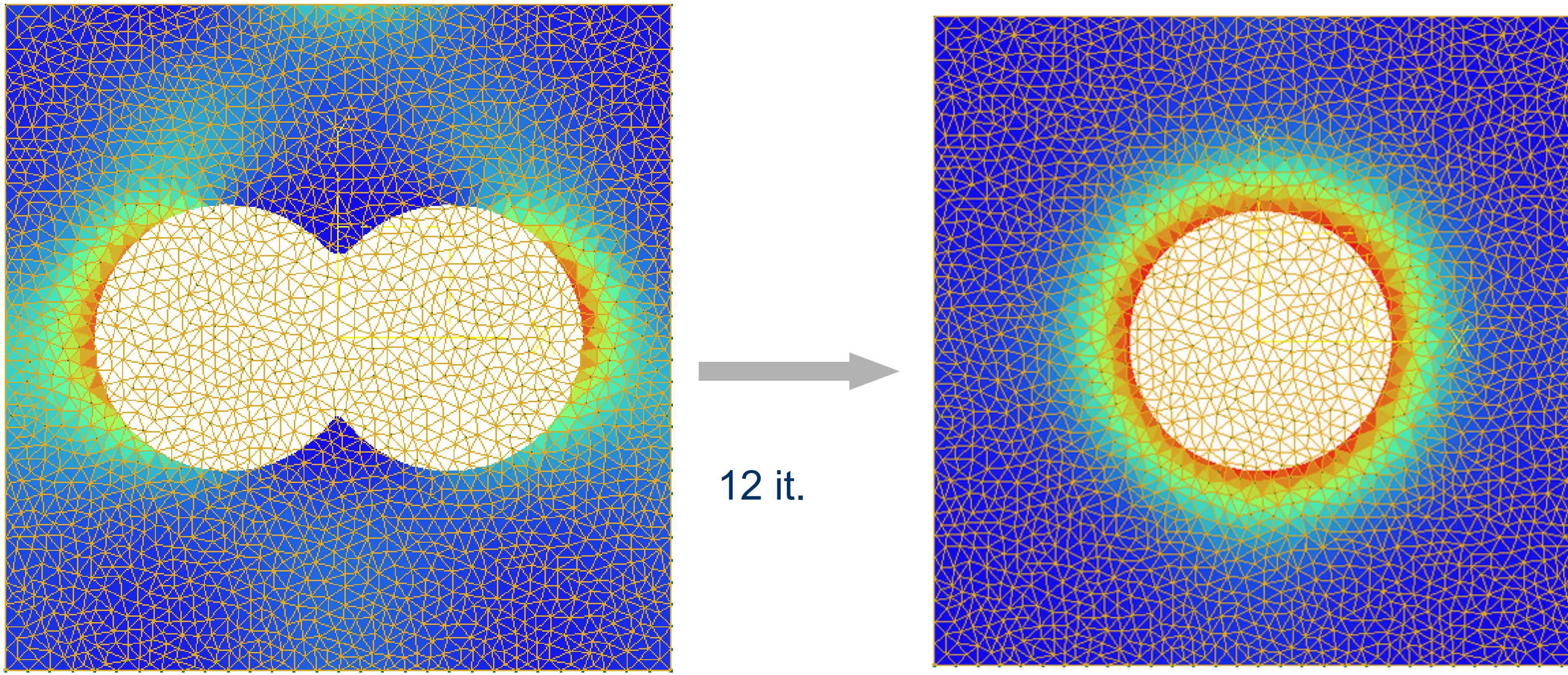


APPLICATIONS



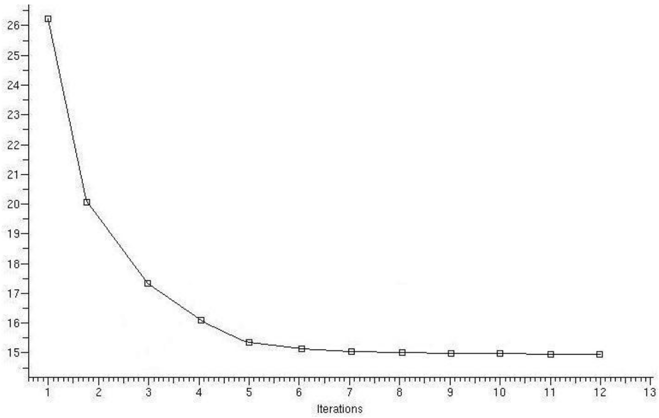
APPLICATIONS

- Toplogy modification during optimization
  - Two variables : *center* x_1, *center* x_2
  - Min. potential energy under a surface constraint
  - Uniform Biaxial loading : $\sigma_x = \sigma_0$, $\sigma_y = \sigma_0$



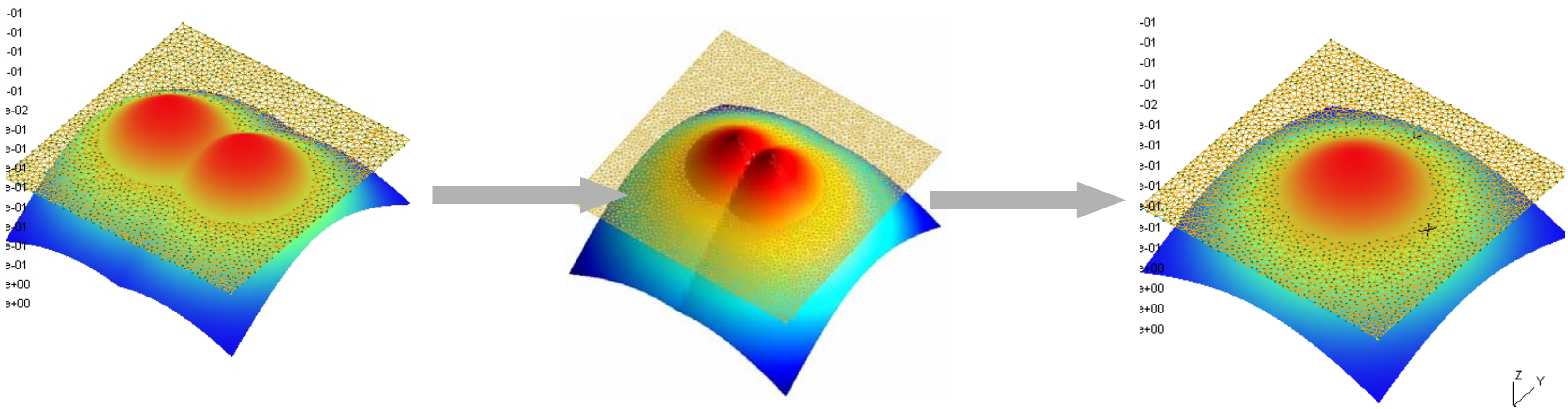
APPLICATIONS

- Evolution of the objective function



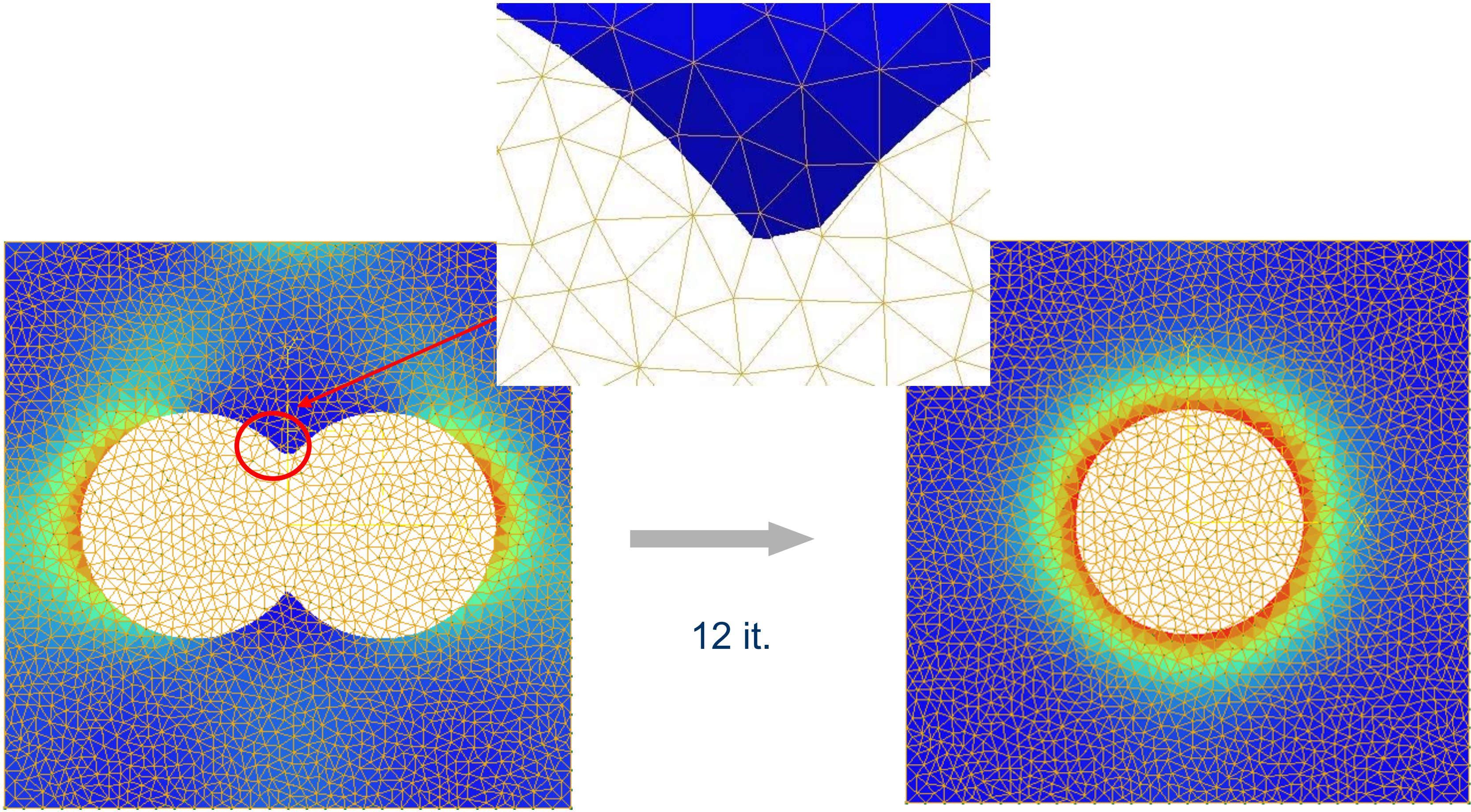
		Iteration 1	Iteration
Objective function	Minimise U	26,6	14,9
Constraint	Surface> 7.8	6.9	7.95
Variable	$-0.5<x_1$ position<0.5	0.5	-0.066207
Variable	$-0.5<x_2$ position<0.5	-0.5	0.045791

- Evolution of the Level Set



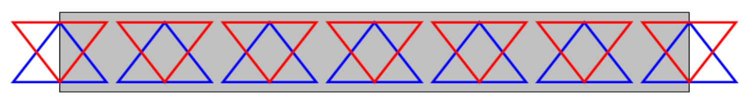
APPLICATIONS

- Mesh refinement for the Level Set representation of sharp parts
- Accuracy of stresses

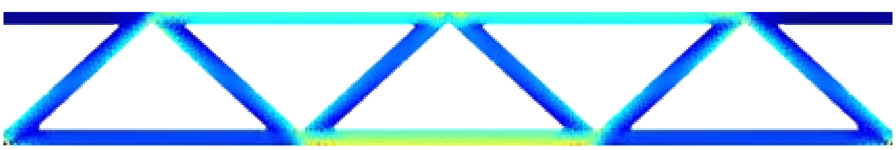


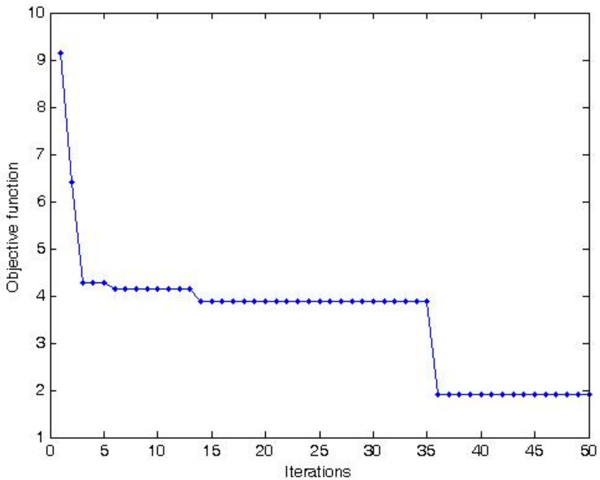
APPLICATIONS

- Design universe of holes (Missoum et al., 2000)
  - Selection and sizing of basic Level Set entities with a GA in classical topology
- Find a result as close as possible to MBB topology solution
  - 14 triangles are « well » placed.
  - Variables : presence of a triangle



- The optimum is reached after 36





CONCLUSION

- XFEM and Level Set gives ride to a generalized shape optimisation technique
- Intermediate to shape and topology optimisation
  - Work on a fixed mesh
  - Topology can be modified:
    - Holes can merge and disappear
    - New holes cannot be introduced without topological derivatives
  - Smooth curves description
  - Void-solid description
  - Small number of design variables
  - Global or local response constraints
  - No velocity field and mesh perturbation problems

CONCLUSION

- Contribution of this work
  - New perspectives of XFEM and Level Set
  - Investigation of semi-analytical approach for sensitivity analysis
  - Implementation in a general C++ multiphysics FE code
- Concept just validated
- Perspectives:
  - Sensitivity analysis (to be continued)
  - 3D problems
  - Stress constrained problems
  - Dynamic problems
  - Multiphysic simulation problems with free interfaces

CONCLUSION

- Thank you for your invitation
- Thank you for your attention

ACKNOWLEDGEMENTS

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  - ARC MEMS, Action de recherche concertée 03/08-298 'Modeling, Multi-physic Simulation, and Optimization of Coupled Problems - Application to Micro-Electro-Mechanical Systems' funded by the Communauté Française de Belgique
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