**To cite this version :**

Franca GIANNINI, Alexei MIKCHEVITECH, Philippe VERON, Bianca FALCIDIENO, Raphael MARC, Jean-Philippe PERNOT, Ruding LOU - Direct modification of FE meshes preserving group information - In: Tools and Methods for Competitive Engineering (TMCE'10), Italie, 2010 - Tools and Methods for Competitive Engineering (TMCE'10) - 2010

# DIRECT MODIFICATION OF FE MESHES PRESERVING GROUP INFORMATION

**Ruding LOU**
Arts et Métiers ParisTech, France
LSIS – UMR CNRS 6168, France
ruding.lou@ensam.fr

**Franca Giannini**
**Bianca Falcidieno**
CNR-IMATI.Ge, Italy
{franca.giannini, bianca.falcidieno}@ge.imati.cnr.it

**Jean-Philippe Pernot**
**Philippe Véron**
Arts et Métiers ParisTech, France
LSIS – UMR CNRS 6168, France
{jean-philippe.pernot, philippe.veron}@ensam.fr

**Alexei Mikchevitch**
**Raphaël Marc**
Electricité de France Group
Research and Development Direction, France
{alexei.mikchevitch, raphael.marc}@edf.fr

## ABSTRACT

*Nowadays, the mainstream methodology for product behavior analysis and improvement relies on the following steps: 1) conceptual solution proposal and CAD prototyping, 2) mesh model creation for Finite Element (FE) analysis, 3) preparation of complex mesh model as specification of semantic information for particular behavior study, 4) advanced FE simulation, 5) result analysis and optimization loops. The semantics relative to the simulation model are often associated to mesh entities through the use of so-called mesh groups. During the optimization phase, geometric modifications are generally performed on the CAD model. This requires a complete updating of the FE mesh model repeating all the above listed FE mesh preparation (re-creation of all the groups). In the present paper, we propose a new framework for CAD-less FE analysis. It comes to apply shape modification operators directly to the FE mesh while exploiting and maintaining the available FE semantic information. As a result, multiple steeps of the design process loop, as CAD and mesh model generation, mesh group creation, are avoided. In this paper, we focus on two 3D mesh modification operators: the planar cracking and the drilling.*

## KEYWORDS

Finite Element analysis, mesh, group, semantics, deformation, crack, hole.

## 1. INTRODUCTION

Numerical behavior simulation is fundamental for new solution assessment in various engineering activities: this allows avoiding physical validation tests. Numerical simulations are generally used during the product development, maintenance or lifecycle problem analysis, and new solution prototyping improving its physical behavior. Such activities are frequently submitted to various constraints crucial from the production point of view. For example, in the maintenance/lifecycle problem analysis context, the main constraints remain with the time and cost of the production process stops. Therefore, it is important to be able to provide fast solutions improving production machinery characteristics as well as satisfying different safety criteria. For example, in the field of power production, it is critical to identify the problem source and to provide the appropriate solution in the shortest time. Thus, experts must have appropriate numerical tools helping to rapidly evaluate various alternative solutions.

Unfortunately, the existing classical methodology for product behavior analysis and solution assessment does not answer to these needs. Today, most of the product behavior analyses rely on the following steps: conceptual solution proposal and its modeling using Computer-Aided Design (CAD) tools, meshing

and preparation of complex mesh models for specific behavior studies, Finite Element (FE) simulation, result evaluation and optimization loops. During the optimization phase, geometric modifications are required and generally performed on the CAD models, thus requiring a re-generation of the FE mesh models corresponding to the new solution. This is done by repeating all the preparation steps necessary for advanced FE Analysis (FEA), i.e. shape adaptation on the CAD level, complex and not totally automatic re-meshing of CAD models (e.g. generation of free/mapped meshes, creation of sub-meshes having different topologies, a priori adaptive mesh, creation of doubles entities, etc.), re-creation of FE entity groups, re-assignment of the semantic information (e.g. Boundary Conditions or BCs, material laws, geometric/mechanical characteristics, etc.).

It is clear that this process is time consuming and therefore inappropriate for fast maintenance analysis. Moreover, in this context, the CAD data are frequently not available or not fully corresponding to the real configuration. Sometimes, data necessary for FE simulation can be obtained though scanning techniques. Thus, the creation of the corresponding CAD models would lead to an additional waste of time and should then be avoided as much as possible.
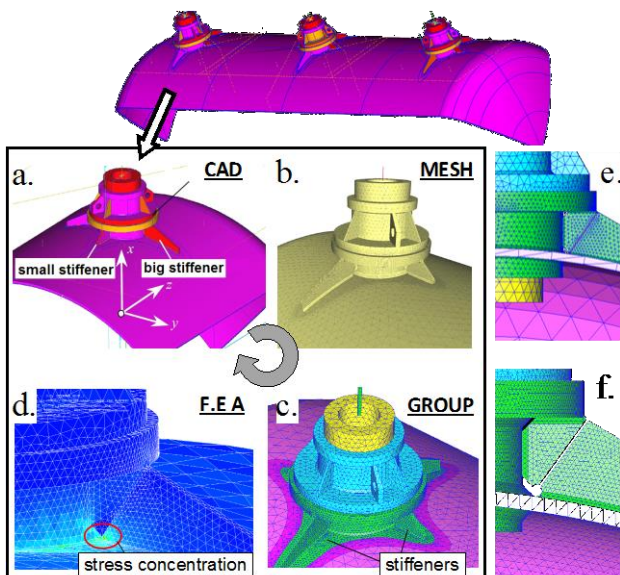


**Figure 1** Mainstream methodology for product behavior analysis and optimization (courtesy EDF-R&D)

Figure 1 illustrates an example of a complex simulation the EDF engineers have to deal with. Starting from a real configuration of a caisson in which a structural modification has to be performed to improve its mechanical behavior, a new solution proto-

typing method would include classically the following steps:

1) creation of the complex CAD model (Figure 1.a), which did not exist, corresponding to a part to be repaired;

2) creation of the mesh model containing 1D, 2D and 3D elements and taking into account different aspects such as mesh quality criteria, mechanical modeling hypotheses for particular FE analysis (Figure 1.b);

3) creation of mesh entity groups on which different FE semantics will be defined (Figure 1.c). Here, 30 mesh entity groups have been created to support semantic data. There exists two ways to create them: either semi-manually by selecting a set of mesh entities and using different criteria or more automatically by selecting the CAD groups of the initial CAD model. This step requires great skill and is time-consuming;

4) FE analysis (Figure 1.d) based on the modeling hypotheses and FE simulation semantics associated to the mesh groups defined in the previous step (3);

5) tuning/validation of the FE model through the comparison of experimental and simulation results;

6) result analysis, modeling optimization, proposal of solutions improving the mechanical behavior of the structure, etc. According to the simulation results, and based on the engineer knowledge, the CAD model can de modified in order to prototype the proposed solution. Here, it involves cracking (Figure 1.e), cutting and drilling the stiffener (Figure 1.f). All the above steps from (1) to (4) are then repeated to validate new simulation hypothesis and the proposed solution.

It seems quite clear that the return to the CAD model is not the most efficient method to implement a local structural modification. This is especially true when the model contains numerous mesh groups for associating a lot of semantic data required for mechanical modeling. For example, some EDF models can contain up to 500 mesh groups dedicated to the FE analysis (e.g. BCs, link relations, different behavior laws, geometric parameters, mechanical modeling of specific phenomena) as well as particular post-processing data. Unfortunately, current commercial CAD systems do not make it possible to automatize the process of direct complex mesh creation and

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modification while preserving such semantic data association. As a consequence, the prototyping/evaluation of structural modifications, even small local changes, requires expensive complete updating of the simulation model that is critical for fast studies.

In order to overcome these limits, we propose a fast prototyping framework working directly at the level of FE mesh enriched by simulation semantics of geometrical nature (mesh groups). This method corresponds to a CAD-less approach allowing the engineer to directly operate on the meshes containing a great number of semantic data already validated with respect to the real counterpart behavior. More precisely, in the present paper, different mesh modification operators are proposed. They work directly on the enriched FE mesh models and allow maintaining and propagating the existing semantic information necessary for FE analysis (e.g. BCs, material attributes, etc. associated to the mesh model via groups of FE entities of different topological dimension, i.e. nodes, edges, faces and/or tetrahedrons). The modifications are driven by a deformation engine that takes into account constraints arising from the geometry of the operators as well as the geometry of the boundaries of the FE groups. Section 2 recalls the philosophy of our multi-layered approach. The geometric operators are introduced in section 3 and additional constraints coming from the use of groups' boundaries are discussed in section 4.

## 2. A MULTILAYERED APPROACH

As illustrated in the previous section, FE analysis requires various data/parameters. This information can be classified according to several levels (Figure 2). The **geometric** data can be considered as the lowest level of information required for FEA. This type of data often describes the shape of the structure to be simulated: it comes to meshed structure. The shape has to be conform to the real geometry of the structure to guarantee an accurate simulation.

At the highest level, FE models include different **semantic** for modeling the physical behavior of the structure: material properties, BCs, interaction with a fluid, etc. For example, in order to characterize the material properties, we use Young's modulus, Poisson's ratio, and material laws. The modeling idealization needs other parameters, for example, a thickness for a thin structure described as a shell. BCs correspond to physical loads of different nature like pressure, concentrated forces, imposed displace-

ments, relationships to simulate a fracture phenomenon or to handle a contact problem, etc.
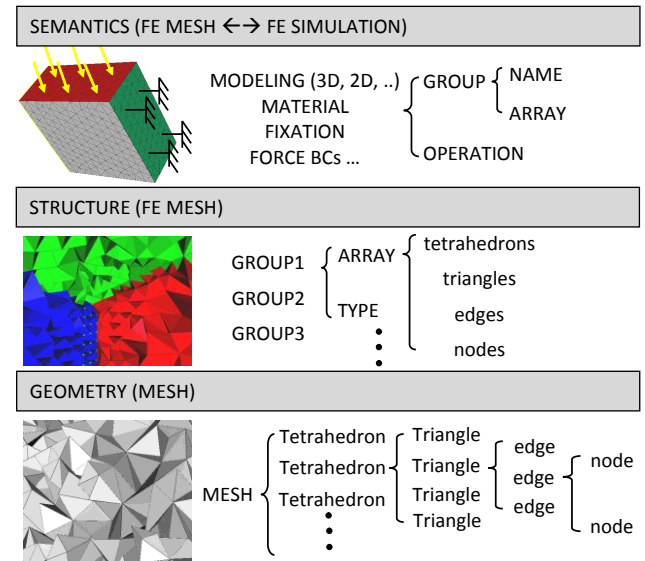


**Figure 2** Three levels of information explored on a FE model.

To be able to relate such semantic data with the discretized geometry, an intermediate layer is needed (Figure 2). This so-called **structural** level maintains the groups (sets) of FE entities (0-3D dimension elements) and allows associating the semantic data to the lower geometric level (e.g. nodes, edges, faces and tetrahedrons in the case of tetrahedron mesh model). For example, a group of tetrahedrons representing a part of a 3D model can be used to specify a particular material law in order to simulate locally a plastic behavior of the structure. A group of triangles can be used to apply the pressure to the structure. A group of edges may idealize a beam-like-shape part. A group of nodes can be used to fix a part of the structure or to describe displacement relations of different nature.

Therefore, during the direct manipulation of FE mesh models containing different structure/semantic data, the mesh modification operators should correctly maintain and update not only the geometry but also all data associated with a given mesh model. Moreover, the associated semantics constrain the FE mesh modification. Thus, effective modification operators should be able to take into account the presented triplet level information (Figure 3).

At the lowest level, the "geometric" one, the proposed mesh operators directly act on the mesh (e.g. position of the nodes, connections between elements, topology) to perform shape modifications. At the middle level, i.e. the "structure" one, the mesh opera-

tors handle the groups of FE elements of any topology. On this level, the operators mainly have to preserve the group definition during the geometric modification. In order to achieve this, the mesh operators detect the key elements of the FE groups to constrain the geometric modification process and so, to restore the group definition after mesh modification. Similarly, on the highest "semantics" level, semantics data has to be handled by mesh operators. Semantic data are both used to set the geometric constraints for mesh modification operators and to specify/update accurately the FE groups.

The aim of the proposed operators is to update correctly all groups in modification zone.
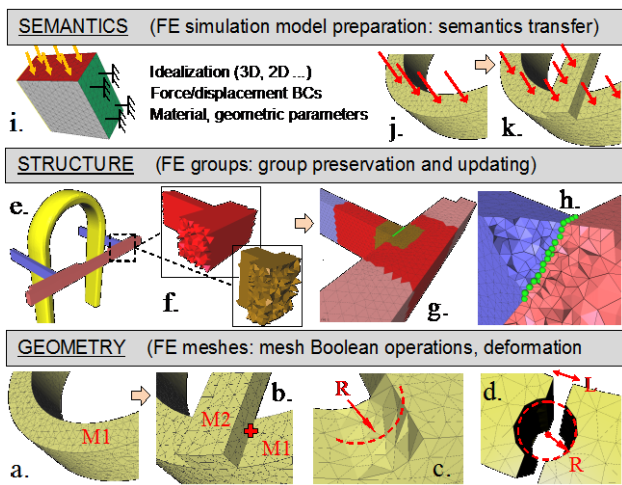


**Figure 3** Overview of CAD-less design operators interacting with three levels of FE mesh data

## 2.1. Different mesh modifications

Mesh modification operators handling 2D/3D FE mesh models can be classified into 3 categories: material addition, material subtraction and material incision operators. Material addition corresponds to mesh merging. Figure 3 presents some examples of 3D mesh modification problem. The Figure 3.a corresponds to the original mesh M1 before any modification. The Figure 3.b shows the result of merging operation: a 3D mesh M2 is fused with the mesh M1. The Figure 3.c illustrates the creation of a fillet on a sharp edge. Here, the cylinder-like shape is obtained by deformation around an initially sharp edge. The Figure 3.d shows two consecutive material subtractions: creation of an incision of width L and drilling of a through hole of radius R.

## 2.2. Proposal of group treatment

We exploit Groups of mesh entities (or FE mesh groups) used to associate FE semantic information to the FE mesh model. FE groups can be used by different FE solvers. For example, the Code_ASTER®, FE solver developed and distributed by EDF R&D, uses currently mesh groups in order to simplify advanced FEA. The "structure" level shown in Figure 3 provides some industrial examples of mesh groups useful for FEA and specific post-processing (courtesy the EDF Group). The Figure 3.e shows a model on which three colored groups of tetrahedrons are defined to associate easily different materials to three components of the given structure. In the zone of contact between the pinkish rod and one of the two blue beams (double nodes are located in this area), there are two other tetrahedron groups (Figure 3.f) useful for particular post-processing of FEA results. Overlapping 3D groups illustrated on the Figure 3.e and the Figure 3.f should be correctly managed during the mesh modification to preserve or propagate the related semantic data. To handle this problem, we propose to decompose groups in non-overlapping groups called "Elementary Groups" (Figure 3.g). The Figure 3.h shows a node group useful for describing a contact problem. The management of overlapping groups of different dimensions is not detailed here (see [2] for more information).

## 2.3. Proposal of mesh operators

Performing shape modifications on meshes may require substituting some elements of the original FE mesh with new ones to guarantee a better quality of the resulting mesh that is a key aspect for FEA. Modifying mesh elements is generally meaningless from visualization point of view, but it may be not in case of updated FE meshes validated from experience or when some of FE elements support mechanical high-level semantics (Figure 3.i, 3.j and 3.k). Thus, in order to maintain and propagate required semantic data, it is necessary to maintain and exploit group information. The associated physical semantics can be also used for defining constraints during the local remeshing or mesh deformation of the FE mesh model.

Based on these considerations, we have developed different mesh modification operators working on the three layers both on 2D and 3D FE meshes. In particular, in this paper we focus on the crack and hole insertion problem.

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## 2.4. Related work

Bremberg and Dhondt [9] propose an approach for crack insertion into the mesh by creating a blending between the surface mesh of the crack profile and the mesh of the cracked volume. The blending needs re-meshing process for intersection between crack profile surface mesh and surface mesh from the hull of the cracked volume mesh, which is for ensuring the shape of the modeled damaged structure. The last is necessary for making two sub-parts in the "cracked" mesh with respect to the crack profile. This approach requires the modeling of the crack as a mesh feature. The main disadvantage of this method is that re-meshing process could be difficult.

Numerical crack introducing and propagation schemes were augmented in an elegant manner with a X-FEM (eXtended Finite Element) method [4,5,6]. The use of special enrichment functions as well as a discontinuous functions along the sides of the crack allows one to achieve "virtually" a complete crack analysis (on mechanical computation level only using so-called "level sets") without any geometric mesh modification [3]. These works aim at predicting crack behavior on the mesh without using CAD model. However, the application of this method could be difficult in the case of geometrically complex cracks having no regular shape (because it is difficult to describe such a crack feature).

In [7,8], the insertion of crack into a mesh model is based on splitting of mesh elements. The direct split of elements could be a very fast process that is crucial for real-time visualization of cracking process. Whereas, from the FEA point of view, the resulting mesh is not appropriate because the split elements could have bad quality. The use of Boolean intersection and cut operations between the original model and crack masks have been presented in [10].

Nienhuys and al. [11] describe a cutting algorithm continuously deforming tetrahedrons so that the cutting trajectory aligns with the tetrahedron face or edge. This method reduces the need to introduce new nodes but can produce degenerate tetrahedrons.

The approach proposed in [12] allows multiple consecutive incisions of tetrahedrons in the crack zone. Tetrahedron maintains its state information including the number and position of cuts. Multiple cuts are merged, and the affected tetrahedrons are subdivided along the cut plane when a portion of the mesh is completely severed from the rest.

In [16][17][18], a cutting mesh approach is proposed and split directly the elements in order to follow the cutting trajectory. However, the mesh quality is not acceptable for FE analysis.

The cutting operators proposed by [14] and [15] take care about the mesh quality but the cutting profile on the mesh does not perfectly match the cutting tool.

In [19], Boolean operations are performed on volume mesh by doing intersection of boundary meshes and completely re-filling tetrahedra. This is not admissible for the case that the tuned FE mesh can be only modified locally.

In [20], a cutting simulation with a mesh of tool and a mesh of operated model is presented. The intersection points between the two interactive meshes are inserted so that the mesh elements are split directly and removed. The cut tool should be meshed and the quality of the result mesh is not enough good for the FE simulation.

In this paper, we present deformation-based cracking and cutting/drilling operations applied to FE mesh while taking into account the presence of mesh groups. Different constraints are created during the mesh deformation in order to preserve the shape of the model as well as the shape of the groups. The next sections are organized as follows: section 3 presents the mesh cracking and cutting operators; section 4 discusses how to handle the mesh groups during the geometry modification operation. Section 5 shows some results on industrial models.

## 3. GEOMETRY OPERATION

### 3.1. Planar crack operator

Cracks are usually idealized as having no volume. The surfaces representing the two sides are distinct but coincident so that nodes on opposite sides of crack faces should have identical coordinates. So, we can speak about double mesh entities (double nodes and face elements), and the model corresponds to a non-manifold mesh. We present a planar crack operator only. This crack is supposed closed at the initial instant to=0.

It can be mentioned that the duplication of nodes and face elements into a volume correspond geometrically to the introduction of the contact zone. Thus, the crack operator discussed in this section can be used to handle the contact problem in the case of planar surfaces in contact.

Our approach is mainly based on three steps: crack interface identification (section 3.1.1), mesh deformation on the level of crack interface (section 3.1.2) and duplication of nodes and faces (section 3.1.3). The crack interface is a set of triangles in case of 3D mesh or a set of edges for 2D mesh. It corresponds to the boundary of the tetrahedrons/triangles lying completely in one side with respect to the crack plane and that have to be deformed to respect this plane. The nodes relative to the interface elements are forced to move onto the crack plane. In order to avoid degenerated triangles/tetrahedrons, some elements not directly in contact with the crack plane are also moved. The deformation process is based on the one presented in [1]. Linear and non-linear constraints required for local mesh deformation can be specified, and the minimization of a quadratic objective function based on a simple mechanical spring/bar-like model provides the final solution in term of local deformation (it comes to mesh relaxation). Indeed, a bar network is created and coupled to the edges of the 2D/3D mesh. Each bar can be seen as a spring with a null initial length and a stiffness. Finally, the crack interface is created by duplicating nodes and faces on the two sides of crack.

These steps are detailed in the following subsections. For sake of clarity, it is supposed that the planar crack affects the entire structure, and that its plane is infinite. In case the crack solely applies locally, additional checks are performed to detect the interface elements really lying in the crack area.

### 3.1.1. Crack Interface identification

This first step separates all the mesh nodes into two sets ($N1$, $N2$) according to their position with respect to the two half-spaces ($P$,$N$) defined by the crack plane.

In the case of 3D mesh, a set $T1$ gathers together the tetrahedra having their 4 nodes belonging to the half-space $P$, respectively $T2$ for tetrahedrons having at least one node in the half-space $N$. Analogously, for 2D mesh, the set $T1$ gathers together triangles whose 3 nodes belong to the half-space $P$, and respectively $T2$ for triangles defined by at least one node belonging to the half-space $N$. The Figure 5.a shows a 3D mesh and the identified sets $T1$ and $T2$ when applying a planar crack.

Now, the Crack Interface (CI) has to be identified. For 3D mesh, the CI is defined as a set of triangles $f$ which are shared by one tetrahedron $t_i$ in $T1$ and one tetrahedron $t_j$ in $T2$. Analogously, in the case of 2D

mesh, the CI is a set of edges $e$ which are shared by one triangle $f_i$ in $T1$ and one triangle $f_j$ in $T2$. Before computing of CI, one of the two sets, let us suppose $T1$, is chosen and processed such that it contains only tetrahedrons (resp. triangles) sharing at maximum one triangle (resp. edge) with tetrahedrons (resp. triangles) of other set $T2$. The set of these triangles/edges will constitute the CI. Actually, tetrahedrons which have 2 or 3 shared triangles (resp. triangles with 2 shared edges) should not take part in the definition of the CI since they will be flattened after the deformation as all CI triangles (resp. edges) will be moved onto a plane (resp. a intersection line between the crack plane and triangle plane).

The processing of the set is performed as follows:

- in the case of 3D mesh, if the tetrahedron in $T1$ has two triangles shared with elements in $T2$, then the edge shared by the other two triangles should be split so that the tetrahedron is subdivided into two sub-tetrahedrons which contain one of the two problematic triangle each. The Figure 4.a shows the tetrahedron △abcd associated with two problematic triangles Δacb and Δadc and the dihedral angle θ that would become 180° after deformation. Here, the edge b-d is split in two by inserting a new node o (Figure 4.b). The tetrahedron is then subdivided into two tetrahedrons △abco and △acdo and each of them has one of the two interface triangles. All neighbor tetrahedrons associating with the split edge b-d should be also split. The Figure 4.c shows all the neighbor tetrahedrons in the original mesh and the Figure 4.d shows them split.

- in the case of 3D mesh, if a tetrahedron in $T1$ contains three triangles shared with tetrahedrons in $T2$, this tetrahedron is moved from $T1$ to $T2$. In this way the fourth triangle becomes an interface triangle.

- in the case of 2D mesh, if a triangle in $T1$ has two edges shared with triangles in $T2$, it should be moved from moved from $T1$ to $T2$. In this way the third edge becomes an interface edge.



(a)   (b)   (c)   (d)

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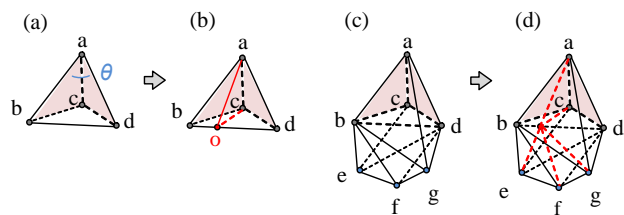
**Figure 4** split schema for tetrahedron with 2 potential interface triangles

### 3.1.2. Crack Interface deformation

Being the elements of the CI defined, a deformation process [1] is applied so that the elements of the CI match the shape of the desired crack. It requires the identification of sets of elements to be moved in a different manner, i.e. using different constraints for each set. We define a set **ICN** (Interior Crack Nodes) constituted by all the interior nodes associated with the elements in **CI** (this is a set of nodes in the interior of the matter) and, a set **ECN** (Exterior Crack Nodes) containing all the exterior nodes associated with the elements in **CI** (this is a set of nodes corresponding to the crack boundary). The Figure 5.a and Figure 5.b show the identified **ICN** and **ECN** nodes in a 3D mesh.

For a tetrahedral mesh, all nodes belonging to only triangles shared by exactly two tetrahedrons are internal, and all nodes associating with at least one triangle which is shared by exactly one tetrahedron are external. For a triangular mesh, all nodes belonging to only edges shared by exactly two triangles are internal, and all nodes associating to at least one edge which is shared by exactly one triangle are external.

To enable a smooth transition between the CI elements and the surroundings, a set of **ITN** (Interior Transition Nodes) is defined. It contains the interior nodes located in the i$^{th}$ neighborhood of the ones in **ICN** and **ECN**. Similarly, a set of **ETN** (Exterior Transition Nodes) is defined and gathers together the exterior nodes located in the i$^{th}$ neighborhood of the nodes in **ICN** and **ECN**. The bandwidth "i" can be user-defined, or it can be computed by dividing the biggest distance between one crack node and the crack plane by the mean edge length. The bigger it is, the smoother the transition will be, and the better the quality of the mesh will be. Figure 5.a and Figure 5.b show **ITN** and **ETN** nodes identified with i = 2.

It can be mentioned that the **ECN** definition can be extended to the case of "finite" crack or contact zone introduction problem in interior of the matter, typically, **ECN** type nodes are absent on crack boundary into the structure and present on the level of external skin of the structure only.

Now that various sets have been identified, geometric constraints can be assigned to drive the deformation process. In the case of 3D mesh, nodes in:

- **ICN** and **ECN** are constrained to stay on the crack plane;
- **ECN** and **ETN** are constrained to stay on the external skin of the 3D mesh;
- **ITN** are free to move;

and all other nodes are fixed.

For 2D mesh, nodes in:

- **ICN** and **ECN** are constrained to stay on the crack plane and on the mesh by preserving its shape;
- **ECN** and **ETN** are constrained to stay on the mesh by preserving its shape;
- **ITN** are constrained to stay on the mesh by preserving its shape;

and all other nodes are fixed.

In case of complex free form shapes, we use a tangent plane to the node to constrain locally the deformation.

During the deformation of the mesh, the deformation engine solves under-constrained set of equations based on the mechanical model of a bar network coupled to the 2D/3D mesh [1]. Additionally, a mesh quality criterion is also used in order to guarantee the quality of deformed mesh from the mechanical FEA point of view.
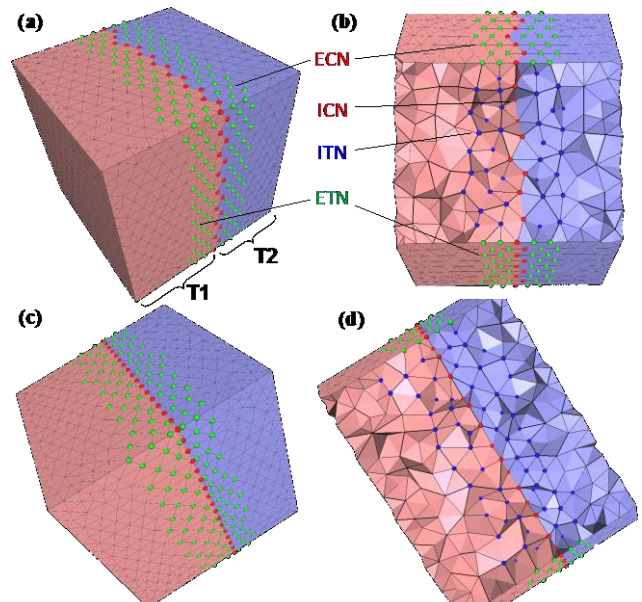


**Figure 5** crack insertion into the 3D mesh of a cube.

### 3.1.3. Definitive crack insertion

In order to complete the insertion of the crack, the mesh entities belonging to the CI are duplicated to separate the mesh into two sub-meshes. Figure 5.c and The Figure 5.d show separately the exterior and the interior of the 3D mesh after insertion of the infinite crack and local mesh deformation in the crack zone.

### 3.2. Through Hole drilling operator

The drilling of a through cylindrical hole is performed in two steps: hole interface creation and its deformation. The Hole Interface is a set **HI** of triangles for 3D mesh (resp. edges for 2D mesh) between the removed mesh elements and the kept mesh elements after cut operation in order to create a through hole. The HI is deformed to match the cylindrical hole shape by using previously adopted deformation engine with new constraints as input [1].

### 3.2.1. Cylindrical HI identification

Similarly to the crack insertion, the nodes are split into two sets which respectively gathers together the nodes inside (**I**) and outside (**O**) of the drilling tool (cylinder).

In the case of 3D mesh (resp. 2D mesh), we define a set **RT** containing all the removed tetrahedrons (resp. triangles) whose four nodes (resp. three nodes) are in the set labeled **I** and, a set **KT** gathering together the remaining tetrahedrons (resp. triangles). For 3D mesh (resp. 2D), a set **HI** is defined by all the triangles (resp. edges) which are exactly shared by one tetrahedron (resp. triangle) in **RT** and one tetrahedron (resp. triangle) in **KT**.

### 3.2.2. Hole drilling

Similarly to the crack insertion problem, the geometric constraints specification will not be the same for all the mesh entities, and an identification of specific node sets to be constrained is required.

First, a set **IHN** (Interior Hole Nodes) gathers together all internal nodes associated with **HI** elements and, a set **EHN** (Exterior Hole Nodes) contains nodes associated with **HI** elements and localized on the external skin of the model. Second, sets **ITN** (Interior Transition Nodes) and **ETN** (Exterior Transition Nodes) are defined similarly to the ones used in the crack insertion problem, i.e. using a bandwidth of ith neighborhood.

The elements corresponding to the hole, **RT** tetrahedrons (resp. RT triangles) are then removed from the mesh model.

Then, geometric constraints can be assigned to different nodes depending on the sets to which they belong. For 3D mesh nodes in:

- **IHN** and **EHN** are constrained to stay on the cylindrical hole;
- **EHN** and **ETN** are constrained to stay on the external skin of the model;
- **ITN** are free to move;

and all the others mesh nodes are fixed.

In the case of 2D mesh, nodes in:

- **IHN** and **EHN** are constrained to stay on the cylindrical hole and on the mesh;
- **EHN** and **ETN** are constrained to stay on the model;
- **ITN** are constrained to stay on the model;

and all the others mesh nodes are fixed.

The constraints being defined, the deformation engine [1] gives a solution in term of local deformation of the drilled hole.
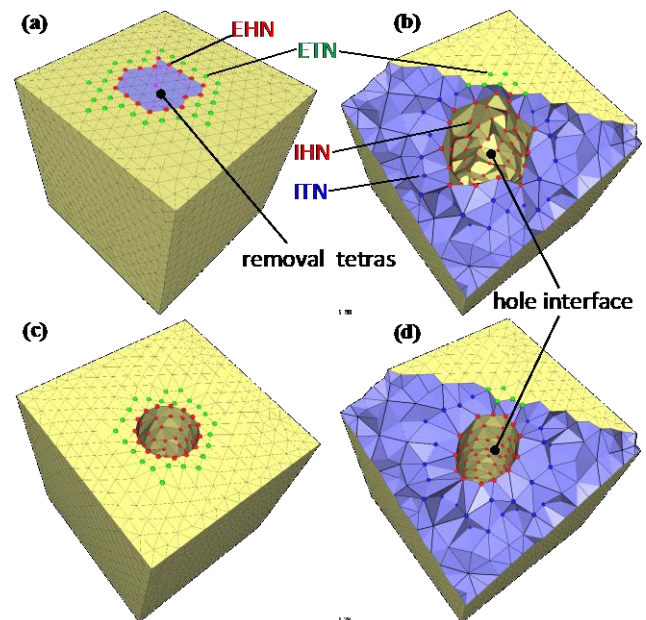


**Figure 6** Creation of a through hole in a 3D mesh.

Figure 6 illustrates the whole process on a cube-like tetrahedral mesh. Figure 6.a and Figure 6.a.b show a mesh model before deformation. First, the removal tetrahedrons (**RT**) and hole interface nodes are iden-

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tified (Figure 6. 6.a). These tetrahedrons are then removed, the newly appearing boundary triangles constitute the **HI** and different node sets used by our technique are identified (Figure 6.b). Next, the constraints are applied, and the solution in term of local deformation of the drilled hole is computed using the deformation engine (Figure 6.c and 6.d).

## 3.3. Extension to two new operators

Based on previously introduced operators, the cylindrical crack and incision/cutting operators can easily be defined and implemented.

Figure 7. a, b, c illustrate the principle of the cylindrical crack operator. Figure 7.a shows an initial mesh on which a cylindrical crack is performed. The profile is defined by a cylinder of center $o$ and radius $r$. In a first step, using an extension of the **HI** identification process, the **CI** is detected (Figure 7.b) and handled similarly to the planar cracks (Figure 7.c).

Figure 7.d, e, f present the principle of the incision operation. Figure 7.d shows an initial mesh on which an incision is performed. The incision is defined by two trimming planes and a distance between them. The first step involves the detection of all the mesh elements which are between the two cutting planes (Figure 7.e). This can be made using an extension of the crack model splitting. Next, the in-between elements are removed, as for cylindrical hole. The two incision interfaces corresponding to the trimming planes are then handled similarly to the crack case (Figure 7.f).
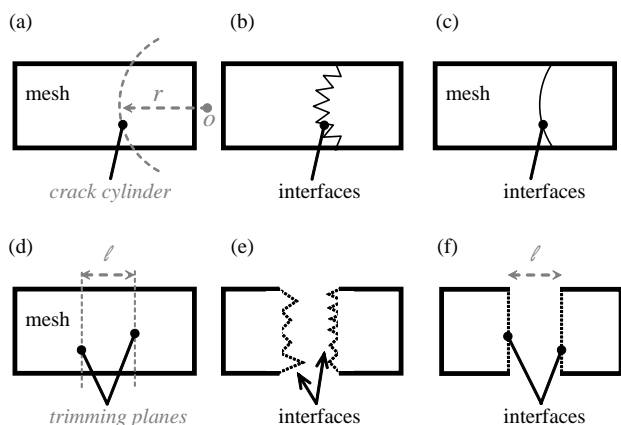


**Figure 7** Overview of the two additional operators: cylindrical crack and cutting/incision operators.

# 4. FE MESH GROUP PRESERVING

## 4.1. On the use of group boundary

Maintaining and propagating semantic information during the mesh modification operation goes through the preserving of FE mesh group called structure level (or low-level geometrical semantics). In particular, this involves an appropriate handling of mesh group geometry: group boundaries (geometrical and "virtual" boundaries), group shapes, topologies (nodes, edges, triangles,…), etc. In this work, we extend the definition and use of the so-called Virtual Group Boundaries (VGB) given in [2]. Roughly speaking, the VGB is defined by a set of 1D and/or 2D elements located at the group frontier enclosing the 0D-3D groups (set of nodes or elements).

Nodes on VGB are used to apply additional constraints during the local deformation to make these nodes staying on the shape of the group boundary.

Figure 8 shows how to apply the mesh operations described in section 3 on a mesh enriched of two groups G1 and G2. The dashed line in Figure 8.a represents the internal limit of the VGB of G1 and G2. Figure 8.b presents the result of removing all elements between the two trimming planes various constraints should be defined on the interface to preserve the planar shape of the cutting planes and the shape of the group boundary. All nodes on the incision interface should be constrained staying on the trimming plane and, in addition, all nodes on the VGB should maintain the geometry of the VGB (should stay on the given shape). The two nodes, which are simultaneously on the incision interface and VGB and represented by circles, have to stay on the trimming planes as well as on the VGB. Moreover, all nodes defining the VGB have to stay on the VGB. Figure 8.c shows the result of the deformation under constraints. Similarly, for crack (Figure 8.d to 8.f) and hole insertion (Figure 8.g to 8.i), specific constraints are assigned to the nodes belonging to the VGB so that the shape of the VGB remains after deformation. This is mandatory to be able to maintain the FE high-level semantic information (like BCs, modeling parameters, material characteristics, etc.) attached to groups G1 and G2.
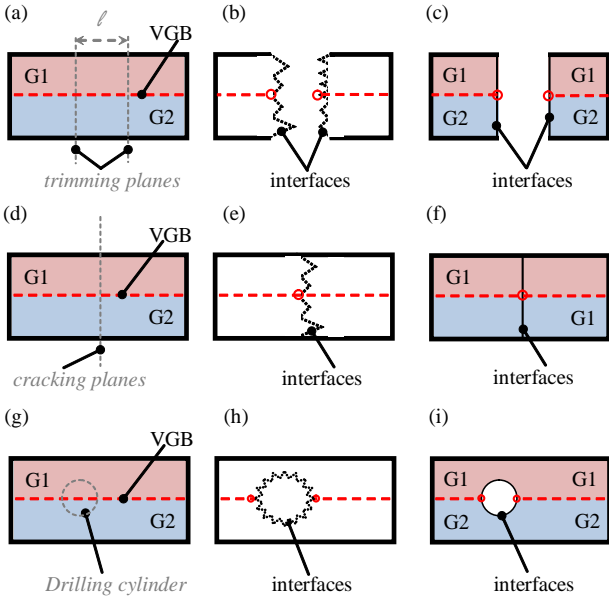
**Figure 8** Incision, crack and hole drilling operators constrained by the shape of the Virtual Group Boundaries.

## 4.2. Extended Group Boundary

The Virtual Group Boundary (VGB) introduced in [2] contains two sets: Bounding Elements (BE) and Isolated Elements (IE). The BE gathers together a set of elements of dimension $d_M - 1$ ($d_M$ being the mesh dimension) enclosing an area of dimension $d_M$. The IE groups mesh entities of dimension lower than $d_M$ which do not cover the area of dimension $d_M$ by themselves. For preservation of group information, depending on the associated mechanical high-level semantics, the area enclosed by BE can be re-meshed, and IE are forbidden to be modified. This concept is quite limit for the case where group of mesh entities have dimension lower than mesh but we want modify them.

Figure 9.a shows an industrial example of mesh union operation: the addition of two stiffeners onto a 2D triangle mesh of a caisson model. In this example, the original mesh contains a group of nodes (Gn) used to define displacement BCs (e.g. fixation of the structure). These nodes also correspond to the geometric boundary of the caisson. When adding a stiffener, a new node has to be inserted between the nodes n1 and n2 (Figure 9.c). Being Gn a group containing all the aligned boundary nodes, it seems meaningful to add the new node in Gn. However, according to the initial definition of VGB [2], all the nodes in Gn are considered as isolated (IE) which prevents the addition of the new node in Gn.
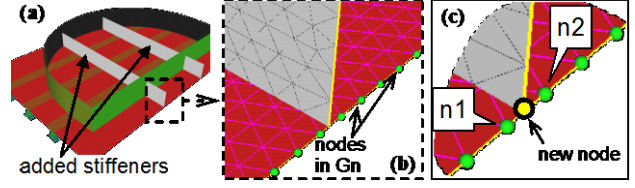


**Figure 9** Example of triangle mesh merging: adding two stiffeners on a caisson (courtesy EDF-R&D)

Therefore, to better handle these kinds of configurations, we extend the VGB definition by enabling the addition of so-called Linking Elements (LE). A LE contains the mesh elements of dimension lower than mesh and higher than node. During the mesh modification, the elements of LE can be split and new elements obtained by splitting can be added to the group. These changes in the VGB structure slightly modify its computation as follows:

- For group of faces in a 2D mesh, the computation of VGB does not change [2].

- For group of edges in a 2D mesh, the computation of BE does not change [2]. All edges defined as isolated in [2] will be put into LE.

- For group of nodes in a 2D mesh, the computation of BE does not change [2]. The set of LE gathers together the edges associated to faces having exactly two group nodes and associated with exactly two group nodes. The set of IE contains the nodes associated to edges having only one node in the group.

- For group of tetrahedrons in a 3D mesh, the computation of VGB does not change [2].

- For group of faces in a 2D mesh, the computation of BE does not change [2]. All faces defined as isolated in [2] will be put into LE.

- For group of edges in a 3D mesh the computation of BE does not change [2]. The set of LE gathers together the triangles which link to tetrahedrons having less than 6 edges (in a given group) and which associate with exactly three group edges. The set of LE also gathers together the group edges which associate with any BE triangles and which associate with exactly 2 nodes in the group. The set of IE contains the nodes associated to edges having only one node in the group.

- For group of nodes in a 3D mesh, the computation of BE is the same as the one presented in the work [2]. The set of LE gathers together the triangles which associated to tetrahedrons hav-

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ing exactly three group nodes and which associate with exactly three group nodes. The set of LE gathers also together the edges which associate with triangles having exactly 2 nodes(in a given group) and which associate with exactly 2 nodes in the group. The set of IE contains the nodes associated to edges having only one node in the group.

As a conclusion, the BE elements enclose an area of dimension equal to mesh. This area can now be re-meshed so that new elements of group dimension can be added to the mesh group. The LE elements cover an area of dimension lower than mesh and more than a node. This dimension area can be split; and new split elements of group dimension can be added to the mesh group.

## 5. RESULTS

This section gives some results relative to the direct modification of industrial 2D/3D FE mesh models using our technique: insertion of different mesh features (crack, hole) following local deformation under constraints taking into account the shape of the group boundaries (low-semantics enriching the FE mesh).
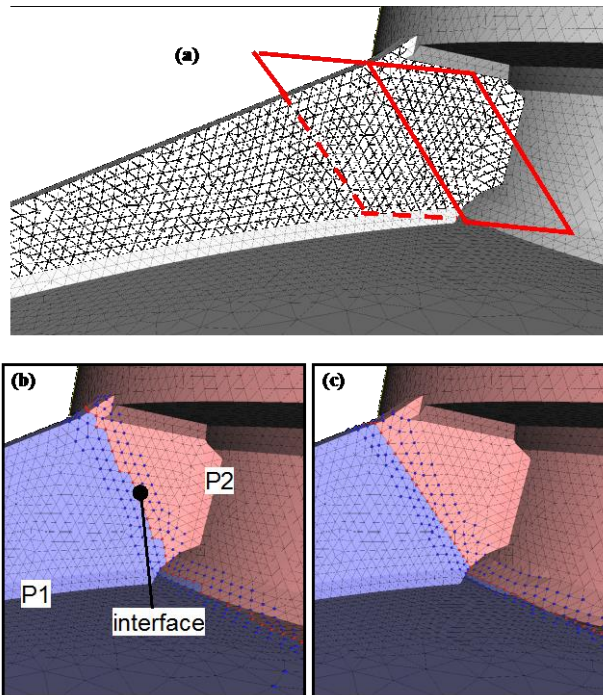


**Figure 10** Insertion of a crack into the 2D mesh of a caisson model generated from a 3D mesh model (courtesy EDF-R&D).

The first example (Figure 10) shows a crack operation performed on a surface mesh of the caisson mesh. Figure 10.a shows a part of the model where one stiffener is located. Figure 10.b corresponds to the preparation step before deformation. The model is divided into two sub-mesh P1 and P2 according to the crack plane, and a crack interface is defined. Figure 10.c presents the mesh after local deformation on the level of crack interface. On this example, 84 nodes have been moved onto the crack plane with 341 nodes moved in order to relax the transition mesh zone between fixed and free nodes. Therefore, 84 crack plane constraints and 425 tangent plane constraints have been used to accomplish accurately the required deformation.

The second example (Figure 11) corresponds to the hole making operation performed on the tetrahedral mesh of the same caisson model. This operation is performed on the stiffener (Figure 11.a). Different mesh entity sets are identified to enable the specification of constraints required for deformation of 3D elements located in the area of the given stiffener (Figure 11.b and Figure 11.c). On this example, 19 nodes have been moved onto the cylinder with 46 nodes moved on their tangent plane and 21 nodes defined as free to move. Therefore, 19 cylinder constraints and 46 plane constraints have been used to accomplish accurately the required deformation.

Another example illustrates the insertion of a cylindrical hole into a cube-like mesh model on which two groups of tetrahedrons are defined. Here, not only it is important to obtain the hole, but also the boundaries of these groups have to be maintained. Figure 12.a shows the initial model on which the tetrahedrons are separated into two mesh groups and shown separately on Figure 12.b and on Figure 12.c. Figure 12.d and Figure 12.f present the result of the through hole drilling operation without taking into account any group boundary. Whereas Figure 12.e and Figure 12.g give the result when preserving the shape of the 3D group boundary using different constraints assigned to corresponding nodes. Red nodes are constrained to stay on the cylinder surface as well as on the group boundary (plane) for those nodes that are on the group boundary (e.g. n1). Blue nodes corresponding to the transition mesh zone are free to move except for those which are on the limit of the two groups and that have to stay on a plane (e.g. n2).
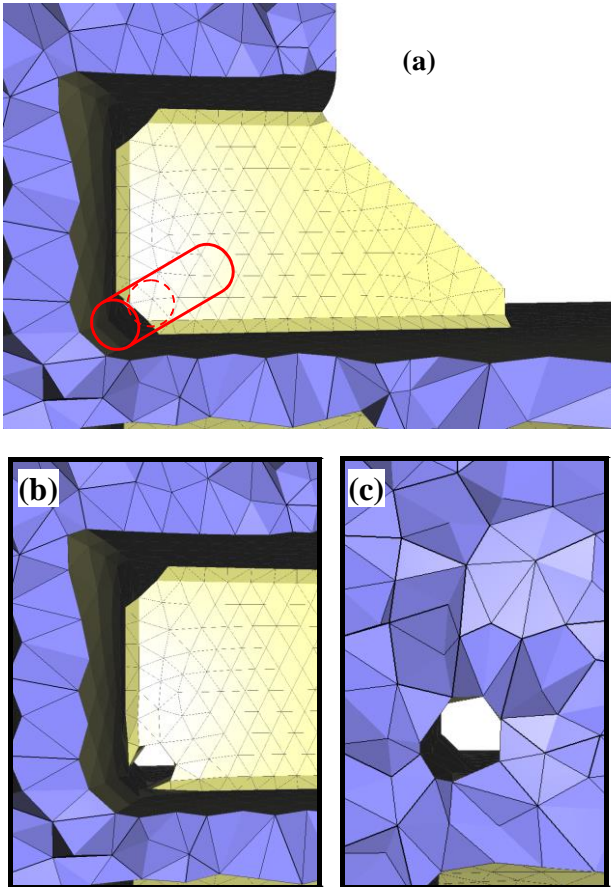
**Figure 11** Insertion of a cylindrical hole into the 3D mesh of a caisson model (courtesy EDF-R&D).

# 6. CONCLUSION AND FUTURE WORKS

In this paper, a new framework for CAD-less FEA has been introduced. Actually, the geometric modifications required during different optimization steps (mesh deformation or various modifications in order to take into account mesh quality criteria) are not anymore performed on the CAD models but directly onto the FE meshes enriched with their (low-, high-level) semantic information through the use of groups.

Several operators have been proposed to cover the primary needs in terms of direct mesh modification: 2D/3D crack and through hole operators. All these operators use a deformation engine using two types of constraints: those relative to the shape of the tools (e.g. cylinder for hole and plane for crack), and those relative to the shape of the group boundaries that have to be preserved. The mesh is modified in a bandwidth so that the quality of the elements (e.g. their aspect ratio) remains good with respect to the FEA requirements. The proposed operators reposition nodes without adding new ones. If the operated

mesh does not have enough nodes in the modification area, a mesh pre-refinement step is necessary.

In the future, we would like to extend our mesh modification toolbox to other shapes (e.g. spheres, torus or free form) as well as to other operators such as material addition which is often required for fast modifying of advanced FE mesh models.
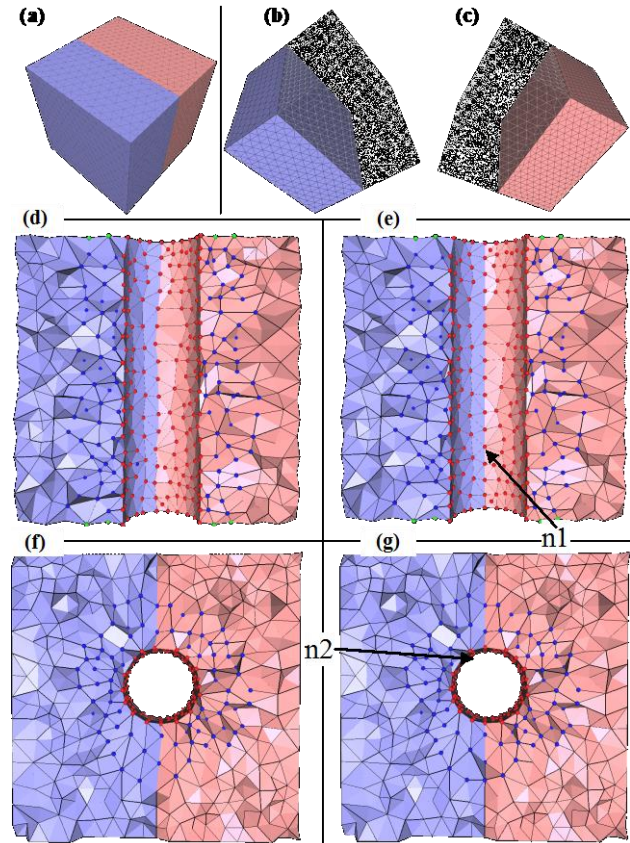


**Figure 12** example of mesh drilling operation by preserving the group boundary

## ACKNOWLEDGMENTS

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