

Chapter 2

Introduction

Due to the developing nature of the cohesive model, this document is supposed to provide guidance on practical application rather than a document written in strict procedural form. As potential users may be less familiar with numerical damage models than with classical fracture mechanics, a brief introduction of the cohesive model is deemed useful and will be provided in this chapter. For more in-depth studies see the fast growing literature in this area, e.g. the papers listed in the Bibliography section.

After the guidelines detailed in [Chap. 3](#), areas of application are described in [Chap. 4](#), some open issues are given in [Chap. 5](#), showing the developing nature of the model and providing hints for further research. According to the experience gained at GKSS, the focus of the present document is on structural assessment, considering structural components made of bulk material and their welds. In an appendix worked examples are demonstrated.

2.1 Motivation for Applying Numerical Damage Models

Structural components containing crack-like flaws, or supposed to contain such flaws, are commonly assessed using the concepts of classical fracture mechanics. These concepts have become mature in the sense that both the characterisation of structural materials and assessment methods have already been cast into national and international standards, standard-like procedures, and codes. A comprehensive overview is given in [1]. However, the limits of classical fracture mechanics came into the focus of structural integrity research as higher exploitation of the mass of an engineering structure became of increasing importance due to the increasing awareness of the limited availability of raw materials and fossil fuel.

In the framework of fracture mechanics, cracked bodies are basically treated in a two-dimensional manner, notwithstanding the fact, that frequently

three-dimensional finite element analyses of test pieces and structural components are performed. The problem is that a fracture mechanics material property, either in terms of a single-valued parameter, commonly known as fracture toughness, or a relationship between the crack extension resistance and the amount of crack extension, is determined under circumstances describing the near-tip stress and strain fields under limiting conditions. These conditions are usually plane strain, more recently plane stress conditions have also been considered to account for the requirements of light-weight structures which are usually characterised by thin walled design [2], see also [3]. However, the conditions a structural component is under are frequently unknown and can substantially deviate from the test conditions for the determination of the fracture properties to be used for the assessment of the component. This problem is known as the transferability problem in classical fracture mechanics.

The advent of numerical damage models is providing a new approach to structural assessment in that these models deal with the damage events in the near-crack tip process zone which are embedded in the global finite element model of the component. This way the global FE model prescribes the loading conditions the component is under onto the damage zone. If the global FE model allows three-dimensional analyses and if the damage model parameters are given as functions of the triaxiality of the stress state, then the transferability problem is ideally solved. The damage models most commonly used can be partitioned into two groups: Models based on micromechanical processes of damage and phenomenological models.

2.1.1 Micromechanics Based Models

For ductile metals, this class of models is based on porous plasticity which describes the effects of nucleation, growth, and coalescence of voids on the load bearing capacity of a material volume as a function of the local stresses acting on that volume. A number of variants of these models have been suggested, see e.g. [4]. Of these, the Gurson–Tvergaard–Needleman model is the most widely used one.

In the case of brittle materials, another problem arises, which is the scatter of the input variables, such that only a failure probability can be given. Deterministic models as summarized here cannot capture this phenomenon and therefore this issue is outside the scope of this document. For further information, refer to [5, 6].

2.1.2 Phenomenological Models

In this group, the models do not depend on a specific failure mechanism and can therefore be used for arbitrary damage. However, the evolution law may indeed be

applicable to a specific class of materials only. Within the group a further distinction can be made by the way of implementation: Models which have a damage law embedded in the continuum formulation are called continuum damage models, whereas the cohesive models do not describe material deformation but only separation. In the following, only cohesive models will be considered for the modelling of damage and failure of materials and structure.

The cohesive model employs a material model [7, 8], which is represented by a traction–separation law describing the loss of load bearing capacity of the material as a function of a separation, irrespective of the physical details of damage occurring in an actual material. Hence, it can be applied to both ductile and brittle damage and failure processes. The absence of mesh dependence—in contrast to porous plasticity models—makes the cohesive models very attractive. A length parameter is already included in the model, the critical separation δ_0 .

Of numerical damage models, the phenomenological cohesive model is the most user friendly one and has a number of advantages. Among other items, numerical robustness, the mesh insensitivity and the need of only two model parameters—as opposed to e.g. up to nine parameters for the ordinary GTN model of porous metal plasticity—make the cohesive model a suitable candidate for practical application.

NOTE It is recommended to read the article in Ref. [9] which contains a fundamental discussion on the nature of the terms “material parameter” and “model parameter”.

2.2 The Cohesive Model

In this chapter, a brief overview of cohesive models and their properties is given. Unless otherwise indicated, the following overview is based on [10]. Cohesive models describe damage and fracture in a wide range of materials at various length and time scales. These materials include metals, polymers, ceramics, concrete, fibre reinforced materials, wood, rock, glass, and others.

As early as 1960, Dugdale [11] introduced a strip—yield model with the idea of a cohesive force preventing a crack from extending. The magnitude of this cohesive force is equal to the yield strength of the material, σ_Y ; strain hardening is not considered, i.e. the material is supposed to behave in an elastic-ideally plastic manner. Since the local stress is limited by the yield strength of the material, the occurrence of a physically unrealistic singularity at the crack tip is avoided, Fig. 2.1. The result of this analysis is the length of the plastic zone ahead of a crack in an infinitely wide sheet subjected to a crack opening Mode I load; it is valid for small scale as well as wide spread yielding until the applied stress reaches the yield strength. Later, Goodier and Field [12] applied the Dugdale model to the

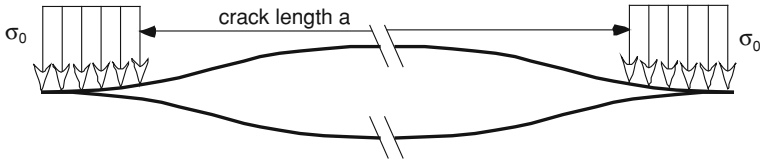


Fig. 2.1 The Dugdale model, after [11]

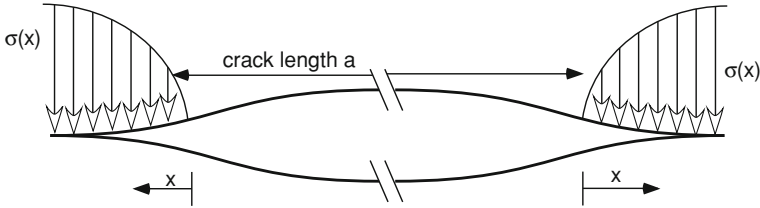


Fig. 2.2 The Barenblatt model, after [14]

determination of the opening profile of the crack including the crack tip opening displacement. Application of the model to a sheet of finite width is also reported [13].

The cohesive models in their present form date back to the work of Barenblatt [14] who replaced the yield strength with a cohesive law to model the decohesion of atomic lattices, Fig. 2.2. This way, the plastic zone was replaced by a process zone within which damage and fracture occur. The detailed processes are

- Plastic deformation;
- Initiation, growth, and coalescence of voids in ductile materials;
- Micro cracking in brittle materials.

Material degradation and separation are concentrated in a discrete plane, represented by cohesive elements which are embedded in the continuum elements representing the test piece or structural component. In both the Dugdale and Barenblatt models, the stresses along the ligament within the process zone do no longer depend on the applied load; they are now a material property. It should be noted that in Barenblatt's model the traction is expressed as a function of the distance from the crack tip, whereas the cohesive models actually in use define the traction as functions of the separation within the cohesive zone. Material degradation and separation are concentrated in a discrete plane, represented by cohesive elements which are embedded in the continuum elements representing the test piece or structural component.

To our knowledge, the first application of the cohesive model to the fracture behaviour of a material was performed by Hillerborg et al. as early as in 1976 [15], who used this model to describe the damage behaviour of concrete. This material has attracted much attention as to its characterisation using the cohesive model, see the work of the research groups of Bažant [16], Carpinteri [17], and Planas and

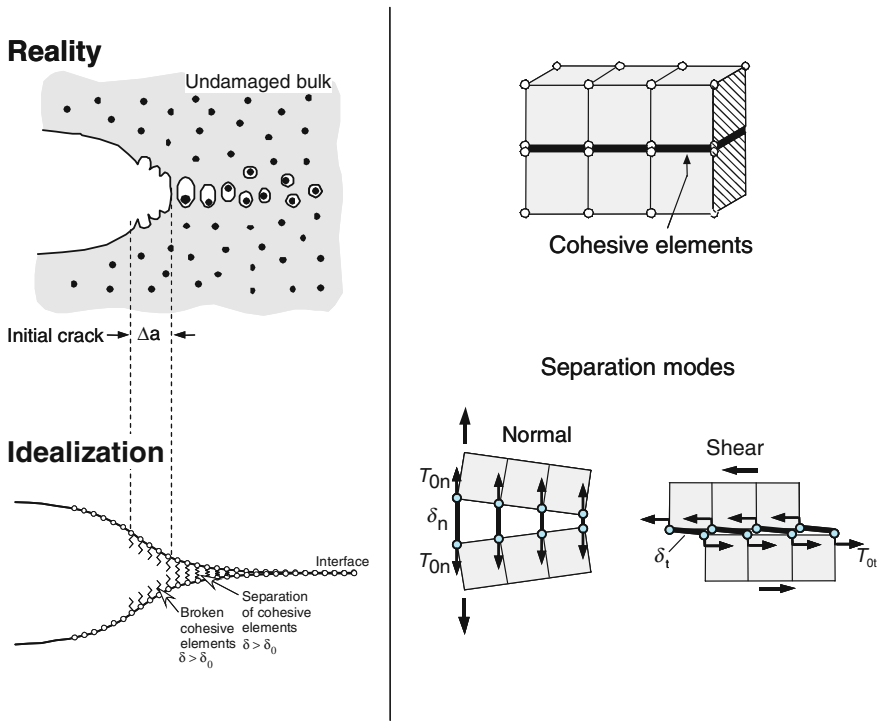


Fig. 2.3 Cohesive model: representation of the physical damage process by separation function within numerical interfaces of zero height—the cohesive elements

Elices [18]. For the other highly important class of engineering materials: metals and their alloys, pioneering work was performed by Needleman, Tvergaard, and Hutchinson. The first analysis of micro damage in ductile materials (particle debonding from a ductile matrix) was performed by Needleman in 1987 [19], and the first macroscopic crack extension in ductile materials was analysed by Tvergaard and Hutchinson [20]. Figure 2.3 shows how the physical process can be represented by the cohesive model. Experimental validation of the cohesive model for ductile materials has been investigated later on, e.g. by Yuan et al. [21]. Further details on applications of cohesive models are given in Chap. 4, for an extensive overview of the cohesive model see [7].

2.2.1 Traction–Separation Law

The constitutive behaviour of the cohesive model is formulated as a traction–separation law (TSL), which relates the traction, T , to the separation, δ , the latter

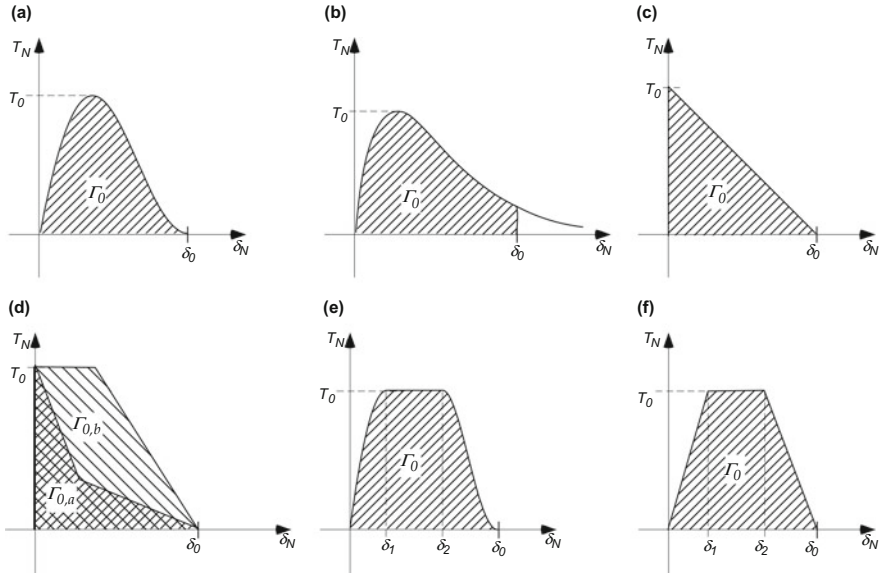


Fig. 2.4 Typical traction–separation laws: **a** Needleman [19], **b** Needleman [30], **c** Hillerborg [15], **d** Bazant [16], **e** Scheider [28], **f** Tvergaard and Hutchinson [20]

representing the displacement jump within the cohesive elements. A cohesive element fails when the separation attains a material specific critical value, δ_0 . The related stress is then zero. The maximum stress reached in a TSL, the cohesive strength, T_0 , is a further material parameter.

A host of traction–separation laws (TSL) have been suggested. (The term “cohesive law” is also being used instead of “traction–separation law”). Figure 2.4 gives an overview of frequently used shapes.

Brittle crack extension analyses of concrete were the first applications of the cohesive model. In purely brittle materials the traction–separation law can be easily identified, since all deformation that is inelastic can be assumed to be material separation. Therefore, the traction–separation behaviour can be determined from a simple uniaxial tensile test, in which the stress state is homogeneous and the elastic deformation can be subtracted from the global structural response. The resulting traction–separation law is often approximated by a linearly decreasing function, see Fig. 2.4c and [15, 22], etc. or by a bilinear function, Figure 2.4d, which has two additional parameters [16, 23].

For ductile metals, a TSL with a finite initial stiffness and a smooth shape as shown in Fig. 2.4a [19, 24], sometimes also with a softening curve approaching a horizontal asymptote and thus approaching zero traction at infinity (Fig. 2.4b), is often used in the literature. Other laws, which are more versatile by introducing additional shape parameters, have also been used.

For a given shape of the TSL, the two parameters, δ_0 and T_0 , are sufficient for modelling the complete separation process. In practice, it has been proven useful

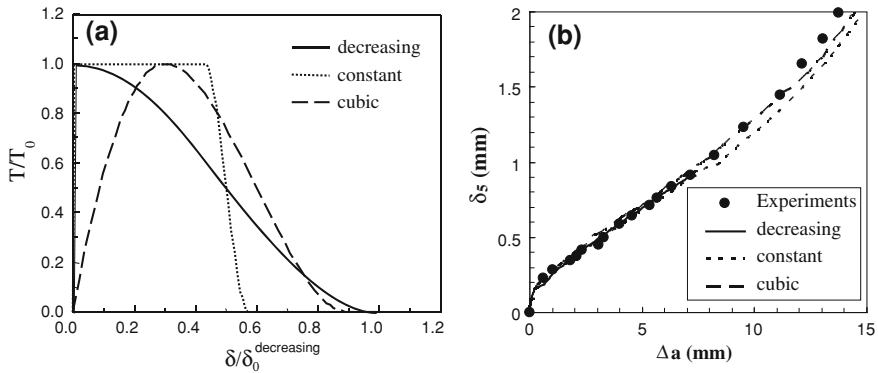


Fig. 2.5 **a** Three TSL's used for simulating a δ_5 R-curve; **b** δ_5 R-curve measured and simulated on a 50 mm wide C(T) specimen made of Al 5083 T321 [25]

to use the cohesive energy, Γ_0 , instead of the critical separation. The cohesive energy is the work needed to create a unit area of fracture surface (in fact twice the unit fracture surface because of the two mating fracture surfaces) and is given by

$$\Gamma_0 = \int_0^{\delta_0} T(\delta) d\delta \quad (2.1)$$

There is a dispute as to whether the traction–separation law should have a finite slope right from the beginning, i.e. also small stresses lead to a material separation, or not. One can see that the shape used for ductile metals has a finite compliance in the beginning as shown in Fig. 2.4a and b, whereas for more brittle materials, Fig. 2.4c and d, the separation is set to zero until a the cohesive strength is reached. In order to avoid an unwanted “elastic” opening of the cohesive element, it is advantageous to have a high stiffness in the beginning. For example, in Fig. 2.4e and f the initial compliance can be defined based on additional shape parameters, which specify the separation at which the cohesive strength is reached.

If a traction–separation law is used, which starts without any separation until the cohesive strength is reached (Fig. 2.4c and d), a contact algorithm must be employed in the implementation of the cohesive element, since conventional elements can never have an infinite stiffness. Therefore, a TSL with a finite stiffness in the beginning is more convenient for implementation into an existing finite element code as a user element,

The choice of the TSL affects the magnitudes of the cohesive parameters, demonstrating the phenomenological nature of the cohesive model. This means that each traction–separation law requires a different set of parameters for a given problem as shown e.g. in [25]. Figure 2.5b shows an experimental δ_5 R-curve with cohesive simulations. It is seen that the three TSL's used, Fig. 2.5a, are able to models the experiment only with different sets of cohesive parameters, Table 2.1.

Table 2.1 Parameters optimised for three TSL's to simulate a δ_5 R-curve of the aluminium alloy 5083 H321 [25]

	T_o (MPa)	δ_o (mm)	Γ_o (kJ/m ²)
Partly constant	560	0.024	10
Polynomial	590	0.043	14
Cubic decreasing	580	0.045	13

2.2.2 Tangential Separation and Mixed Mode Fracture

In the case of mixed mode loading, a tangential separation mode, usually designated Mode II and Mode III, accompanies the normally considered crack opening, Mode I. In linear elastic fracture mechanics, a phase angle, Ψ_{LEFM} , can be defined

$$\Psi_{LEFM} = \arctan \left[\frac{K_{II}}{K_I} \right] \quad (2.2)$$

where K_I and K_{II} denote the stress intensity factors for crack opening Modes I and II, respectively. In the context of the cohesive model, a tangential displacement, δ_t , represents the additional shear mode and is superimposed to the displacement normal to the crack plane (or plane of expected damage in the absence of a pre-existing crack), δ_n . In analogy to Eq. (2.2), a phase angle for the cohesive model reads [26]

$$\Psi = \arctan \left[\frac{\delta_t}{\delta_n} \right] \quad (2.3)$$

Alternatively, the phase angle can be expressed in terms of the energy release rate corresponding to the cohesive energy by re-formulating Eq. (2.2)

$$\Psi = \arctan \sqrt{\frac{G_{II}}{G_I}} \quad (2.4)$$

In general the resulting displacement can be obtained from

$$\delta_{res} = \sqrt{\delta_n^2 + \delta_t^2} \quad (2.5)$$

It must be noted that there are almost as many mixed mode formulations for the cohesive model as traction–separation laws. If the simple formulation, Eq. (2.5), is used for an “effective” separation, the resulting traction in normal and tangential directions is calculated by

$$\mathbf{T} = T(\delta_{\text{eff}}) \left(\frac{\delta_N}{\delta} \mathbf{n} + \frac{\delta_t}{\delta} \mathbf{t} \right) \quad (2.6)$$

in which $\mathbf{n}$ and $\mathbf{s}$ are the normal and the tangential unit vectors of the cohesive element, respectively. A similar formulation is given by an additional weighting

factor β for the tangential separation in Eq. (2.6) as introduced by [22], which then leads to

$$\mathbf{T} = T(\delta_{\text{eff}}) \left(\frac{\delta_N}{\delta} \mathbf{n} + \beta^2 \frac{\delta_t}{\delta} \mathbf{t} \right) \quad (2.7)$$

Other formulations for the interaction of separation modes work without an effective separation, but with an explicit dependence on both the normal and the tangential separations, as e.g. developed by [27]:

$$\begin{aligned} T_N &= T_0 e \exp\left(-\frac{\delta_N}{\delta_0}\right) \left[\frac{\delta_N}{\delta_0} \exp\left(-\frac{\delta_T}{\delta_0}\right)^2 + (1-q) \left[1 - \exp\left(-\frac{\delta_T}{\delta_0}\right)^2 \right] \frac{\delta_N}{\delta_0} \right] \\ T_T &= 2T_0 e q \left(\frac{\delta_T}{\delta_0} \right) \left(1 + \frac{\delta_N}{\delta_0} \right) \exp\left(-\frac{\delta_N}{\delta_0}\right) \exp\left(-\frac{\delta_T}{\delta_0}\right)^2 \end{aligned} \quad (2.8)$$

An even more variable approach has been presented by [28], in which a multiplicative decomposition of the dependence on the separation components is used:

$$\begin{aligned} T_N &= T_{N,0} f(\delta_N) g(\delta_T) \\ T_T &= T_{T,0} f(\delta_T) g(\delta_N) \end{aligned} \quad (2.9)$$

In this case, the formulation for the shape of the TSL in the one-dimensional case, $f(\delta)$, is fully decoupled from the interaction function $g(\delta)$ and can be chosen independently.

It is worth noting that mixed mode loading causes path dependency, i.e. damage depends on how the two modes are activated during the loading process.

2.2.3 Cohesive Elements

This document considers cohesive elements as interface elements with two surfaces, which usually lie on top of each other in the undeformed state, i.e. they do not span a volume. If, however, the two surfaces have a finite distance in between, the resulting volume does not have any physical meaning, since it is not the strain in the element that is the relevant quantity, but the displacement jump between the surfaces. In order not to replace any real material by cohesive interface, the volume of the cohesive elements should be as small as possible and negligible compared to any other dimension in the model. In the framework of the finite element method, they have to be implemented corresponding to the surrounding continuum model, i.e. if the structure is modelled by 3D continuum elements, the cohesive elements must consist of surfaces as shown in Fig. 2.6a, if the structure is modelled in 2D or shell elements the cohesive elements reduce to line elements, see Fig. 2.6b and c. The difference between cohesive elements for plane strain/plane stress and shell structures is that the latter are defined in the three dimensional space. Therefore, any separation may be in-plane or out of plane, and the in-plane direction must be defined by the user, which can be done by a fifth node as shown in Fig. 2.6c.

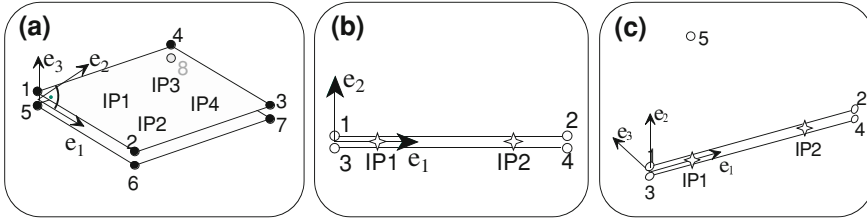


Fig. 2.6 Cohesive element library for 3D FE models (a), for plane stress/strain models (b), and for shell models (c)

Several commercial FEM solvers offer cohesive elements in their libraries. However, these elements are usually available for a subset of structural problems only, for example only for plane 2D and 3D problems, but not for shell meshes, etc.

2.2.4 Commercial Solutions for Cohesive Elements

The preferred method is to use those commercial codes such as ABAQUS, ANSYS, Marc, Zebulon and Warp 3D, which do already include cohesive elements. These elements are verified and tested, it is assumed that the simulation with these elements is robust and stable, and pre-processors can be used for their generation.

On the other hand, some features, which are being investigated in the scientific community, are not yet available in commercial codes. Usually, only a subset of element types can be used in combination with cohesive elements, and the number of possible traction–separation laws is limited as well. In many cases, a specific class of applications was intended when implementing the cohesive elements. To the authors' knowledge, no commercial code provides cohesive elements for shells.

Table 2.2 gives a short overview of some present implementations of cohesive elements in commercial finite element systems as well as the element types and traction separation laws available.

NOTE For those users wishing to use their own elements or a finite element code without cohesive elements guidance is given in [29].

2.2.5 Crack Path

The cohesive elements embedded in the finite element model of the component to be assessed prescribe the path of crack extension. However, if the path a pre-existing crack is going to take is not known a priori cohesive elements have to be

Table 2.2 Commercial codes providing cohesive elements in their element libraries

Code	Cohesive elements for these structures	Traction–separation laws	Mixed mode	Remarks
ABAQUS	2D, 3D	Linearly decreasing, exponentially decreasing, tabular	Yes	Intended mainly for delamination
ANSYS	2D, 3D	Exponential (Needleman potential)	Yes	
MARC	2D, 3D	Bilinearly and exponentially decreasing function		Intended mainly for delamination
WARP3D	3D	Needleman potential	Yes	
Nastran	2D, 3D	Bilinearly, exponentially and exponentially decreasing function		Intended mainly for delamination
Zebulon	2D, 3D	Needleman potential	Yes	Incl. automatic contact activation after complete debonding
FRANC2D	2D	Linearly and bilinearly decreasing, exponentially decreasing		

placed anywhere the crack may chose its path, so that a specific array of cohesive elements becomes active and hence defines the crack path which reaches the failure conditions prior to the other arrays placed in the neighbourhood of the crack tip, Fig. 2.7. Consequently, it seems appropriate to equip every crack problem with as many possible crack paths as possible in order to avoid false predictions of the crack path. However, the amount of computational effort increases with the number of elements, and the choice of the crack path is not really arbitrary, since the most appropriate mesh is one consisting of triangles. Beside the large number of cohesive elements needed for such a simulation, the zigzagging path may cause numerical problems and lead to a mixed mode separation where in the real material a pure normal separation occurs. An additional problem arises when a TSL with an initial compliance is used. In this case, the total deformation even at small loads depends strongly on the compliance itself and the number of cohesive elements in loading direction, since all elements separate slightly in a homogeneous stress state.

2.2.6 Further Functionalities

For different classes of materials, a dependence of the cohesive parameters on various field quantities must be taken into account. Two examples are ductile

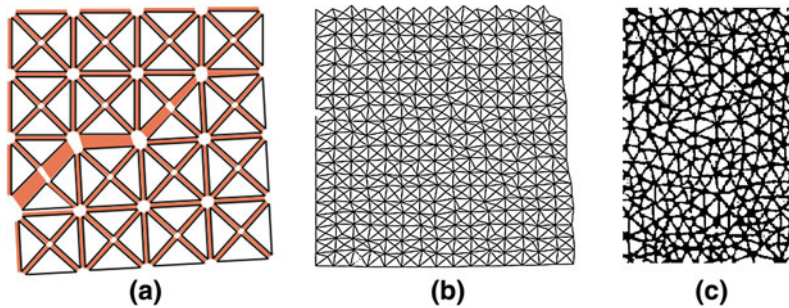


Fig. 2.7 Sketch showing meshes with cohesive elements between all boundaries of continuum elements; (a) is a regular mesh; (b) and (c) are irregular meshes. The mesh in (b) is derived by moving the nodes from mesh (a) randomly, whereas the nodes in mesh (c) are generated randomly

materials, where the cohesive parameters depend on the degree of triaxiality, or adhesives and plastics, for which the damage behaviour is strongly dependent on the local strain rate. Since cohesive elements do not account for either triaxiality or strain rate, these values must be imposed by the surrounding finite element model of the configuration considered. As in-depth studies are still lacking it is at present not possible to provide a systematic picture of these effects. Some hints will be given in [Chap. 5](#).

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