A. Tables of symbols

In this appendix, we recall the meaning of the main symbols used in this book, with the number of the page where their definition is introduced (when relevant). We recall that Latin dummy indices implicitly vary between 1 and 3, whereas Greek dummy indices implicitly vary between 1 and 2.

We point out that the same notation may be used to refer to different quantities provided that there is no possible confusion in a given context.

A.1 Latin Symbols

	Symbol, meaning and page number	
A^{3Ds}	bilinear form in the 3D-shell model	130
A_h^{3Ds}	id. with approximate geometry	256
A^B	bilinear form in the basic model	125
A^K	bilinear form in the m-b model	123
A^N	bilinear form in the s-m-b model	114
A_{b}	scaled bending virtual work	137
A_{b}^{3Ds}	id. in 3D-shell model	193
A_{m}	scaled membrane (and shear if any) virtual work	137
A_{m}^{3Ds}	id. in 3D-shell model	193
A^{3D}	3D plane-stress internal virtual work	228
A_h^{3D}	id. with approximate geometry	230
a	determinant of matrix $(a_{\alpha\beta})$	27
$\underline{\underline{a}}$	first fundamental form	26
$\vec{a}_1, \vec{a}_2$	2D covariant basis	25

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Symbol, meaning and page number		
$\vec{a}^1, \vec{a}^2$	2D contravariant basis	25
$\vec{a}_3$	unit normal vector	24
$\underline{\underline{b}}$	second fundamental form	27
$\underline{\underline{c}}$	third fundamental form	30
C, c	generic positive constants	
$C^{\alpha\beta\lambda\mu}$	plane-stress in-plane constitutive coef.	101
${}^0_4C$	shell in-plane constitutive tensor	103
d	depth of beam structure	261
$D^{\alpha\lambda}$	plane-stress transverse constitutive coef.	101
${}^0\underline{\underline{D}}$	shell transverse constitutive tensor	103
dS	surface infinitesimal	27
dV	volume infinitesimal	19
E	Young's modulus	
$\vec{\vec{e}}$	3D linearized strain tensor	96
F^{3Ds}	linear form in the 3D-shell model	130
F_h^{3Ds}	id. with approximate geometry	256
F^B	linear form in the basic model	125
F^K	linear form in the m-b model	123
F^N	linear form in the s-m-b model	114
F^ε	generic external virtual work	137
F^{3D}	3D external virtual work	228
F_h^{3D}	id. with approximate geometry	230
G	scaled external virtual work	138
$\vec{\vec{g}}$	3D metric tensor	13
g	determinant of matrix (g_{mn})	19
$\vec{g}_1, \vec{g}_2, \vec{g}_3$	3D covariant basis	17
$\vec{g}^1, \vec{g}^2, \vec{g}^3$	3D contravariant basis	19

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Symbol, meaning and page number		
H	mean curvature	29
H^p	Sobolev space of order p	50
${}^{(4)}H$	Hooke's law tensor	100
h	mesh parameter	60
K	Gaussian curvature	29
k	shear correction factor	104
L	overall characteristic dimension	136
L^2	fundamental Sobolev space	48
L_1, L_2	Lamé constants	100
l	thickness profile	136
p	approximation order of the FE shape functions	223
q^ε	scaled shear force in Timoshenko beam	267
$\underline{q}^\varepsilon$	scaled shear force in RM plate	278
R_h	reduction operator	295
(r, s)	tangential local coordinates	228
$\vec{x}_1, \vec{x}_2, \vec{x}_3$	reference orthonormal basis	25
t	thickness of the shell	24
$t_{\min}$	minimum thickness	121
U^ε	generic shell solution for given ε	137
U^0	generic limit bending solution	142
U^{m}	generic limit membrane solution	147
$\vec{U}$	3D displacement solution	95
$\vec{U}_h$	3D displacement FE-solution	230
$\vec{u}$	midsurface displacement solution	95
$\vec{u}_h$	midsurface displacement FE-solution	230
V	generic shell displacement test function	137
$\vec{V}$	3D displacement test function	102

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	Symbol, meaning and page number	
$\vec{v}$	midsurface displacement test function	95
$T, \tilde{T}$	original/scaled tip load in Timoshenko beam	261
z	transverse local coordinate	228

A.2 Greek Symbols

	Symbol, meaning and page number	
δ_m^n	Kronecker symbol	
$\underline{\underline{\epsilon}}$	symmetrized gradient tensor	117
ε	non-dimensional thickness parameter	136
$\underline{\eta}, \vec{\eta}$	rotation test function	102
$\vec{\varPhi}$	3D chart	17
$\vec{\phi}$	surface chart	24
$\bar{\varGamma}_{nm}^k$	3D Christoffel symbols	21
$\varGamma_{\beta\alpha}^\lambda$	surface Christoffel symbols	31
γ	generic *strictly positive* constant	
$\underline{\underline{\gamma}}$	membrane strain tensor	97
$\lambda_i(r, s)$	2D finite element shape function	228
ν	Poisson's ratio	
$\varOmega$	3D reference domain	17
ω	surface reference domain	24
π	projection operator onto tangential plane	232
$\underline{\underline{\bar{\rho}}}$	linearized change of curvature tensor	106
ρ	scaling exponent for loading	138
$\vec{\vec{\sigma}}$	3D stress tensor	
$\underline{\theta}, \vec{\theta}$	rotation solution	95

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Symbol, meaning and page number		
$\vec{\theta}_h$	rotation FE-solution	230
ξ^1, ξ^2, ξ^3	curvilinear coordinates	17
$\underline{\underline{\chi}}$	bending strain tensor	97
$\underline{\zeta}$	shear strain tensor	97

A.3 Special Symbols

Symbol, meaning and page number		
$\mathcal{B}$	3D shell body	24
$\mathcal{BC}$	boundary conditions	
$\mathcal{E}$	Euclidean (physical) space	9
$\mathcal{I}$	FE-interpolation operator	232
$\mathbb{R}$	set of real numbers	
$\mathcal{S}$	shell midsurface	24
$\mathcal{T}$	generic stress space in mixed formulations	62
$\mathcal{T}^+$	generic L^2-type stress space	74
$\mathcal{T}^{RM}$	shear space in RM-plate model	279
$\mathcal{T}_h^{RM}$	FE shear space in RM-plate model	283
$\mathcal{T}^T$	shear space in Timoshenko model	267
$\mathcal{T}_h^T$	FE shear space in Timoshenko model	270
$\mathcal{V}$	generic shell displacement space	137
$\mathcal{V}^{3D}$	3D displ. space (shell domain)	228
$\mathcal{V}_h^{3D}$	3D FE displ. space	229
$\mathcal{V}^{3Ds}$	displ. space in the 3D-shell model	130
$\mathcal{V}^B$	displ. space in the basic model	125
$\mathcal{V}^G$	displ. space for general Reissner-Mindlin kinematics	231

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Symbol, meaning and page number		
$\mathcal{V}_h^G$	general shell element displ. space	232
$\mathcal{V}^K$	displ. space in the m-b model	123
$\mathcal{V}^N$	displ. space in the s-m-b model	114
$\mathcal{V}^{RM}$	displ. space in Reissner-Mindlin plate model	277
$\mathcal{V}^T$	displ. space in Timoshenko model	261
$\mathcal{V}_h^T$	FE displ. space in Timoshenko model	262
$\mathcal{V}_0$	generic subspace of pure bending displ.	141
$\mathcal{V}^{3Ds}$	pure bending subspace in 3D-shell model	192
$\mathcal{V}_0^K$	pure bending subspace in m-b model	152
$\mathcal{V}_0^N$	pure bending subspace in s-m-b model	152
$\mathcal{V}_0^T$	pure bending subspace in Timoshenko model	261

B. Some Useful Mathematical Formulas

We first recall an elementary bound.

Proposition B.1 *For any two real numbers a and b, we have*

$$|ab| \leq \frac{1}{2}\left(\eta\, a^2 + \frac{1}{\eta}\, b^2\right), \qquad \forall \eta > 0. \tag{B.1}$$

Proof. This inequality directly follows from the positiveness of the expressions $\left(\sqrt{\eta}\, a + b/\sqrt{\eta}\right)^2$ and $\left(\sqrt{\eta}\, a - b/\sqrt{\eta}\right)^2$. ■

The following result is very useful when manipulating norms in product spaces.

Proposition B.2 *For any set of n real numbers $(a_i)_{1 \leq i \leq n}$, we have*

$$\frac{1}{\sqrt{n}} \sum_{i=1}^{n} |a_i| \leq \left(\sum_{i=1}^{n} (a_i)^2\right)^{\frac{1}{2}} \leq \sum_{i=1}^{n} |a_i|. \tag{B.2}$$

Proof. Noting that (B.2) expresses the equivalence of two norms in $\mathbb{R}^n$, the equivalence itself directly follows because all norms are equivalent in finite-dimensional vector spaces, hence

$$\gamma \sum_{i=1}^{n} |a_i| \leq \left(\sum_{i=1}^{n} (a_i)^2\right)^{\frac{1}{2}} \leq C \sum_{i=1}^{n} |a_i|, \tag{B.3}$$

for *some constants* γ and C. In order to obtain actual values for these constants, we develop

$$\begin{aligned}\left(\sum_{i=1}^{n}|a_i|\right)^2 &= \sum_{i=1}^{n}(a_i)^2 + 2\sum_{1\le i<j\le n}|a_i a_j| \\ &\le \sum_{i=1}^{n}(a_i)^2 + \sum_{1\le i<j\le n}(|a_i|^2 + |a_j|^2) \\ &\le n\sum_{i=1}^{n}(a_i)^2, \end{aligned} \tag{B.4}$$

where we have used (B.1) with $a = a_i$, $b = a_j$ and $\eta = 1$, and the fact that each given index appears exactly $(n-1)$ times in a summation over $1 \le i < j \le n$. The other inequality directly follows from the first line of (B.4). We can see that these bounding constants are sharp by choosing all numbers equal for C, and all numbers but one equal to zero for γ. We also see how the equivalence "degenerates" (with the growth of $\sqrt{n}$) when the dimension of the vector space increases. ■

C. Distributions: Basic Definitions and Properties

This appendix aims at recalling the fundamental concepts and results of the theory of distributions that are strictly necessary for the understanding of our discussions in this book. For more details, we refer to (Schwartz, 1966; Dautray & Lions, 1988–1993).

Considering an open set $\mathcal{O}$ in $\mathbb{R}^n$, we denote by $C_0^\infty(\mathcal{O})$ the space of indefinitely differentiable functions with compact support in $\mathcal{O}$ (namely, each function vanishes outside of a compact subset of $\mathcal{O}$). In addition, for any compact subset Q we denote by C_Q^∞ the space of functions of $C_0^\infty(\mathcal{O})$ that vanish outside of Q.

Given a linear real-valued operator ϕ defined on $C_0^\infty(\mathcal{O})$, we say that ϕ is a *distribution* in $\mathcal{O}$ if, for any compact subset Q of $\mathcal{O}$, there exist an integer p and a constant C such that

$$\boxed{\forall u \in C_Q^\infty, \qquad |\phi(u)| \leq C \sup_{\xi \in Q,\, |\mathbf{m}| \leq p} |\partial_{\mathbf{m}} u(\xi)|.} \tag{C.1}$$

Note that the integer p reflects the regularity of the distribution, namely, with a lower p the distribution is more regular. The space of all distributions in $\mathcal{O}$ is a vector space that we denote by $\mathcal{D}'(\mathcal{O})$. In the sequel, we denote the action of distributions on functions of $C_0^\infty(\mathcal{O})$ by

$$\langle \phi, u \rangle_{\mathcal{D}'(\mathcal{O}) \times C_0^\infty(\mathcal{O})} = \phi(u). \tag{C.2}$$

We point out that the notation $\mathcal{D}(\mathcal{O})$ is also often found instead of $C_0^\infty(\mathcal{O})$ in the literature.

We now give some basic examples of distributions.

Example C.1

Consider a continuous function f defined in $\mathcal{O}$, and any function $u \in C_Q^\infty$ for Q arbitrary. We have

$$\left| \int_{\mathcal{O}} f u \, d\mathcal{O} \right| \leq \left(\int_{\mathcal{O}} |f| \, d\mathcal{O} \right) \sup_{\xi \in Q} |u(\xi)|, \tag{C.3}$$

hence f defines a distribution through

$$\langle f, u \rangle_{\mathcal{D}'(\mathcal{O})\times C_0^\infty(\mathcal{O})} = \int_{\mathcal{O}} f u \, d\mathcal{O}. \tag{C.4}$$

In fact, the use of integration such as in this equation is the basic means of constructing distributions based on regular functions. ■

The following example shows that distributions can be built using less regular functions.

Example C.2
Consider $\phi \in L^2(\mathcal{O})$ and take, for any compact subset Q of $\mathcal{O}$, a function $u \in C_Q^\infty$. Clearly $u \in L^2(\mathcal{O})$, and by the Cauchy-Schwarz inequality we have

$$\left| \int_{\mathcal{O}} \phi u \, d\mathcal{O} \right| \leq \|\phi\|_{L^2(\mathcal{O})} \left(\int_{\mathcal{O}} u^2 \, d\mathcal{O} \right)^{\frac{1}{2}} \leq \|\phi\|_{L^2(\mathcal{O})} \sqrt{|Q|} \sup_{\xi \in Q} |u(\xi)|. \tag{C.5}$$

Hence, ϕ defines a distribution by

$$\langle \phi, u \rangle_{\mathcal{D}'(\mathcal{O})\times C_0^\infty(\mathcal{O})} = \int_{\mathcal{O}} \phi u \, d\mathcal{O} \tag{C.6}$$

and therefore we can write

$$L^2(\mathcal{O}) \subset \mathcal{D}'(\mathcal{O}). \tag{C.7}$$

Of course, this inclusion also holds for higher-order Sobolev spaces, recall (3.52). ■

We can also define distributions without resorting to actual functions, as can be seen in the next example.

Example C.3
Consider the Dirac delta "function". Assuming that $\mathcal{O}$ contains 0, by definition for any function u in C_Q^∞ we have $\delta(u) = u(0)$. Therefore

$$|\delta(u)| \leq \sup_{\xi \in Q} |u(\xi)|, \tag{C.8}$$

and the delta "function" thus defines a distribution. Clearly, this distribution is not a function (since it cannot be defined by its point values), which is why we used quotes above. It is – indeed – one of the primary objectives of distributions to extend the classical functional framework. ■

We now come to the definition of differentiation for distributions. Considering a C^1 function f, the classical derivatives of f are distributions, see Example C.1, and we have for any u in $C_0^\infty(\mathcal{O})$

$$\begin{aligned}\langle \frac{\partial f}{\partial \xi^i}, u \rangle_{\mathcal{D}'(\mathcal{O})\times C_0^\infty(\mathcal{O})} &= \int_{\mathcal{O}} \frac{\partial f}{\partial \xi^i} u \, d\mathcal{O} \\ &= -\int_{\mathcal{O}} f \frac{\partial u}{\partial \xi^i} \, d\mathcal{O} \\ &= -\langle f, \frac{\partial u}{\partial \xi^i} \rangle_{\mathcal{D}'(\mathcal{O})\times C_0^\infty(\mathcal{O})}, \end{aligned} \tag{C.9}$$

where we have used Green's formula. Note that the last expression in (C.9) can be written because $\frac{\partial u}{\partial \xi^i}$ is also in $C_0^\infty(\mathcal{O})$. The general definition of the derivatives of a distribution is a direct extension of this identity. Namely, for any distribution ϕ in $\mathcal{D}'(\mathcal{O})$ we define $\frac{\partial \phi}{\partial \xi^i}$ as the distribution given by, for any $u \in C_0^\infty(\mathcal{O})$,

$$\boxed{\langle \frac{\partial \phi}{\partial \xi^i}, u \rangle_{\mathcal{D}'(\mathcal{O})\times C_0^\infty(\mathcal{O})} = -\langle \phi, \frac{\partial u}{\partial \xi^i} \rangle_{\mathcal{D}'(\mathcal{O})\times C_0^\infty(\mathcal{O})},} \tag{C.10}$$

and it is – indeed – easily seen that $\frac{\partial \phi}{\partial \xi^i}$ thus-defined fulfills the above definition property of distributions.

We demonstrate the power and the flexibility of this extended differentiation concept in the following example.

Example C.4

Assume that $\mathcal{O}$ is bounded and consider the variational problem

Find u in $H_0^1(\mathcal{O})$ such that

$$\int_{\mathcal{O}} \vec{\nabla} u \cdot \vec{\nabla} v \, d\mathcal{O} = \int_{\mathcal{O}} f v \, d\mathcal{O}, \qquad \forall v \in H_0^1(\mathcal{O}), \tag{C.11}$$

where $f \in L^2(\mathcal{O})$. We know from Chapter 3 that this problem has a unique solution. Of course $C_0^\infty(\mathcal{O}) \subset H_0^1(\mathcal{O})$, and considering an arbitrary test function $v \in C_0^\infty(\mathcal{O})$ we obtain

$$\begin{aligned}\int_{\mathcal{O}} \vec{\nabla} u \cdot \vec{\nabla} v \, d\mathcal{O} &= \sum_{i=1}^{n} \langle \frac{\partial u}{\partial \xi^i}, \frac{\partial v}{\partial \xi^i} \rangle_{\mathcal{D}'(\mathcal{O})\times C_0^\infty(\mathcal{O})} \\ &= -\langle \Delta u, v \rangle_{\mathcal{D}'(\mathcal{O})\times C_0^\infty(\mathcal{O})}, \end{aligned} \tag{C.12}$$

using the above rule of differentiation of distributions. Also

$$\int_{\mathcal{O}} f v \, d\mathcal{O} = \langle f, v \rangle_{\mathcal{D}'(\mathcal{O})\times C_0^\infty(\mathcal{O})}. \tag{C.13}$$

We infer that

$$-\Delta u = f, \tag{C.14}$$

where the equality holds in the distribution sense (note that Δu is not *a priori* in L^2, since u is only in H^1). Conversely, if we seek u in $H_0^1(\mathcal{O})$ that satisfies (C.14) we – of course – obtain by the same chain of equalities that

$$\int_{\mathcal{O}} \vec{\nabla} u \cdot \vec{\nabla} v \, d\mathcal{O} = \int_{\mathcal{O}} f v \, d\mathcal{O}, \tag{C.15}$$

for any $v \in C_0^\infty(\mathcal{O})$. Therefore, since $C_0^\infty(\mathcal{O})$ is dense in $H_0^1(\mathcal{O})$ (Adams, 1975), we infer that (C.11) holds. Finally, we found that the two equations (C.11) and (C.14) are equivalent (when seeking a solution in $H_0^1(\mathcal{O})$). For comments regarding the physical meaning of the equivalence, we refer to (Bathe, 1996). ■

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