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Three-dimensional nonlinear finite element model of lumbar intervertebral disc

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The main objective of this study is to model a three-dimensional nonlinear finite-element vertebra disc, which can be used in further simulation of human lumbar spinal segments in surgery, analyses of spinal equilibrium and stability. Because of complexity of modelling it is proposed to carry out analyses on the simplified model built in such a way that the nonlinear response of the disc is replaced by a spring-type behaviour whose characteristics are obtained by computer simulations of an isolated disc. The geometry data of a human lumbar spinal segment, including a disc, is acquired from the computer tomography or magnetic nuclear resonance measurements, and a CAD model is designed and imported into FEA program. The simplified model was validated for loading schemes, including axial compression, bending and torsion acting on the spinal L4-L5 segment. Two models of intervertebra disc are shown and theirs advantages and accuracy are discussed.

Key words: biomechanics, nonlinear FEA, lumbar spine

1. Introduction

The complexity of carrying out numerical simulations of human lumbar spinal segment is rather obvious [2]–[4]. It arises from complexity of its geometry, difficulties in defining material properties (bones, ligaments etc.) and simplifications which have to be done according to recognition of boundary conditions. The experimental verification made on the living system is not easy either; it has rather qualitative and integrated character.

The intervertebral disc and ligaments play the essential role in the spine kinematics and contribute to general stiffness of spinal segment [1]. It exhibits pronounced time-dependent deformations when subjected to load variations. These deformations are caused by fluid that flows to and from the disc and by viscoelastic deformation of annulus fibrous. The fluid flow is due to the differences between mechanical and osmotic pressure.

The intervertebral disc is composed of three different parts. The essential component of the intervertebral disc is the annulus fibrous. It consists of 10–20 sheets of collagen called a lamellar collagen. Superior and inferior vertebral endplates are the other components of the intervertebral disc. These are the plates of cartilage that covers the superior and inferior aspects of the disc and binds the disc to their respective vertebral bodies. Besides enabling bending movements between vertebral bodies, the intervertebral disc allows twisting and small sliding movements. Their amplitudes depend on elasticity and tensile stiffness of the annulus.

2. The aim of the study

The aim of the study was to develop and validate the simplified model of the intervertebral disc and further the whole lumbar spinal motion segment. This simplification is based on replacement of the disc by a connector-type element, whose elasticity behaviour is spring-like in available components of relative motion. If nonlinear behaviour is required, a force or moment versus relative displacement or rotation can be specified. Alternatively 12 by 12 elasticity matrix (as a function of field variables) can be given. It was applied in our studies. To follow this approach and to reach the goal that leads to this crucial simplification of the spine model we have to examine first the disc (figure 2) which is subjected to six loading schemes: axial compression, shearing in two directions, bending in two planes and torsion. By applying the unit loads (axial, shear and moments) and recording displacements at the appropriate points, where relative motion is estimated, a compliance matrix and then the stiffness matrix of the disc can be built. In the range of our interest, i.e. small rotations and small displacements, a tangent stiffness matrix can be used because of the assumed linearity of load–displacement relations.

In order to design a computational model of the spinal motion segment, we need some precise geometrical data of the real object. Besides topology, the additional data such as volume density, surface texture, etc. can be of interest. Different methods of acquisition of geometrical data can be used. They may be obtained with contact scanners and non-contact scanners. These methods are described in detail in [13], [16], [19]. The geometry data of a human lumbar spinal segment, including a disc, was collected using the computer tomography and magnetic nuclear resonance. The CAD model was developed and imported into FEA commercial code ABAQUS and meshed. A final result of meshing is shown in figure 1.

3. FEA modelling

The structure and properties of the spinal motion segment analyzed are complex. The first step taken to allow simulation of the behaviour of biomechanical system is a proper definition of the model geometry. In the kinematics of the spinal motion segment, intervertebral disc and ligaments play the most essential role. In this study, we focused our attention on a proper modelling of disc in numerical simulation of L4–L5 segment. The FEA model of motion segment is shown in figure 1.

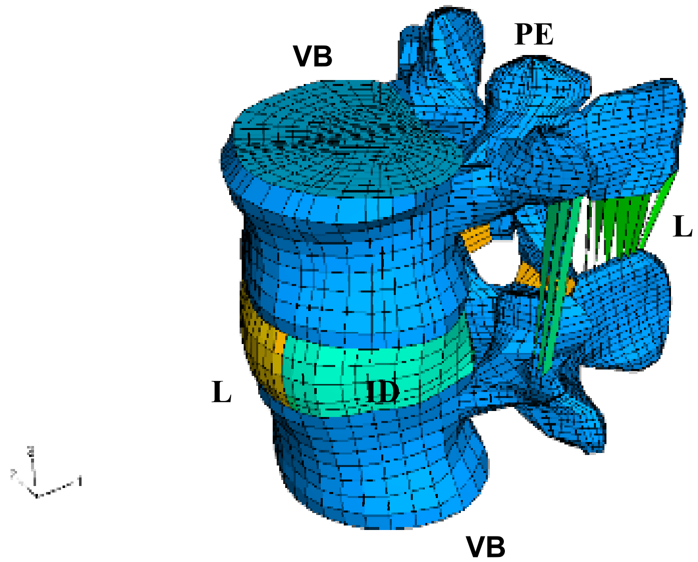

Fig. 1. FE model of human lumbar spinal segment:
VB – vertebral bodies, ID – intervertebral disc, L – ligaments, PE – posterior elements

The annulus fibrous of the intervertebral disc is a highly structured material made up of alternating tissue layers with collagen fibers oriented at +30° and –30° with respect to the circumferential axis. The disc can be modelled as anisotropic material of hyperelastic properties [4] or by structural elements which induce this anisotropy. The ground matrix of the disc annulus is modelled by 3D solid elements. The collagen fibers can be modelled by truss elements carrying only tensile stresses [6] and by rebar type elements embedded in 3D solid elements. When using the first approach each truss element in each layer of the annulus fibrous has to be connected with 3D solid element nodes in such a way as to keep up the orientation mentioned above (figure 2a). Development of such a model is a quite tedious and time-consuming occupation. Additionally, this approach is mesh-dependent because any remeshing requires re-defining the data concerning truss elements (their orientation and properties). In the present study, the second method was employed which has some advantages over the previous one being mentioned above.

The rebar elements are uniaxial reinforcements in solid elements which can be defined as surface layers (figure 2b) with uniformly spaced reinforcing bars. Such layers are treated as smeared layers of a constant thickness equal to the area of each reinforcing bar divided by the reinforcing bar spacing. This approach allows ease altering the number of layers, section properties and section orientation and is independent of element re-meshing. The calibration of the 3D embedded elements by means of published data [9] was performed in our study by selecting an appropriate number of fibers (rebars) with their cross-sectional areas. The nucleus pulposus, assumed here as an incompressible body, was modelled as fluid-filled cavity using hydrostatic fluid elements with initial pressure equal to 2 MPa [9]. Hydrostatic fluid elements cover the boundaries of the nucleus pulposus. They share the nodes at the cavity boundary with the standard elements of annulus fibrous.

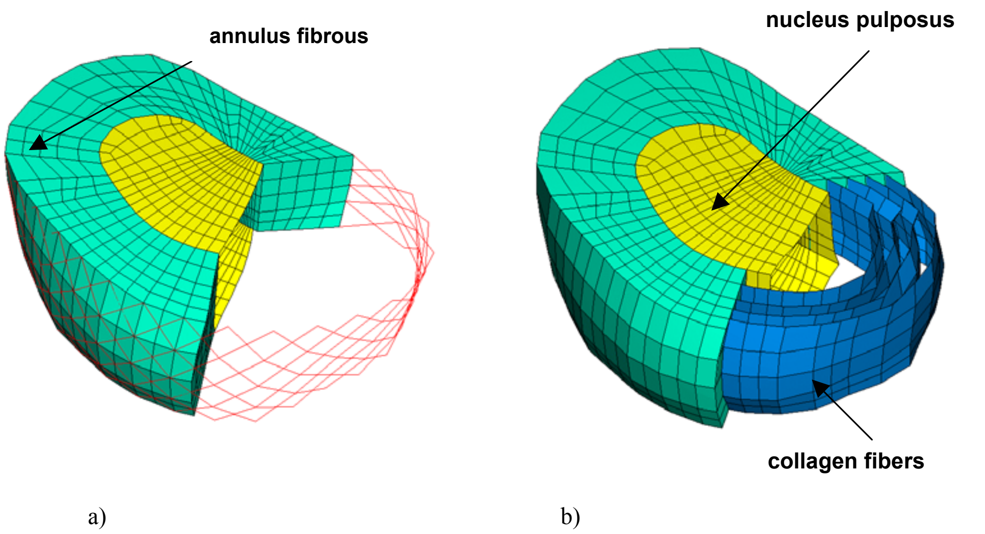

Fig. 2. FE models of intervertebral disc:
a) with truss elements, b) with surfaces or rebar layers

Selected constitutive data used in the model of a disc for further computations are summarized in table 1.

Table 1. Material properties of disc components

Anatomic part	Material	Properties	
Endplates	isotropic	$E = 23.8$ MPa	$\nu = 0.4$
Annulus fibrous – ground matrix	isotropic	$E = 4.0$ MPa	$\nu = 0.4$
Annulus fibrous – fibers	isotropic, no compression	$E = 45$ MPa	–
Nucleus pulposus – incompressible body	incompressible fluid	$\rho = 1.0\text{E}{-6}$ kg/mm^3	–
Ligaments	isotropic	$E = 6$–12 Mpa	–

4. FE analysis

A basic idea of the simplification of a motion segment modelling is to replace the complex structure of the intervertebral disc by one connector-type element of complex properties. The elastic behaviour of the element of this type can be described as equivalent stiffness matrix that has in general case the form of **F** = **KD**, where **F** is the vector (12 components) of generalized forces that act on the segment, **D** is the vector (12 components) of mutual displacements between bones, and **K** (12×12 matrix) is the stiffness operator of the segment. The values of these matrix components were obtained based on FEA simulations. For the behaviour of the segment in the range of our interest, i.e. small rotations and small displacements, a tangent stiffness matrix was used because of assumed linearity of load displacement relations. In order to follow this approach, the isolated disc, which was subjected to twelve loading schemes, was examind in the first place. By means of applying the unit loads (axial, shear and moments) and recording displacements at the appropriate points, where relative motion was estimated, a compliance matrix and then the stiffness matrix were built for the model. Four concepts of connector elements were tested. The first three were based on a two-node, twelve dof (six transverse and six rotational) element whose behaviour was described by means of 12 by 12 stiffness matrix. Three definitions of this matrix were prepared: the full matrix with 144 non-zero components, the reduced matrix with 92 significant non-zero components and the symmetrized matrix with 52 non-zero components. The last one was based on a special type of connector element. It was a two-node element with 6 by 6 stiffness matrix. This matrix described relative movements and rotations of these two nodes (table 2). The last stage was the comparison of the numerical models of motion segments containing one element of intervertebral disc with a model containing a multi-element, complex disc definition. All four concepts of the equivalent element were studied. The six load cases discussed above were taken into consideration (figure 3). The recorded relative displacements and rotations allowed validation of different concepts of intervertebral disc simplifications.

The loads were applied to the reference point which coupled all points lying on the upper surface of the disc, while the bottom surface of the disc was protected against any movement. Recorded relative displacements allowed us to build the compliance matrix and then the stiffness matrix as an inverse operator. The comparison of different concepts of modelling disc is given in table 2.

Table 2. Comparison of disc simplification

Complex FE model	One-element model with symmetrized matrix	One-element model with full matrix
• 5 types of elements: solid, membrane, • shell, rebars, fluid • ~ 4000 elements • ~ 9000 dof • 136 sec/iteration*	• 1 type of element • 12×12 stiffness matrix **K** • 52 non-zero components • 1 element • 6 dof • 1 sec/iteration*	• 1 type of element • 12×12 unsymmetrized stiffness matrix **K** • 144 non-zero components • 1 element • 6 dof • 1 sec/iteration*

One-element model with reduced matrix	Connector element model
• 1 type of element • 12×12 unsymmetrized stiffness matrix **K** • 92 non-zero components • 1 element • 6 dof • 1 sec/iteration	• 1 type of element • 6×6 symmetrized stiffness matrix **K** • 18 components • 1 element • 6 dof • 1 sec/iteration*

* CPU time on P4, 2 GHz, 512 MB RAM.

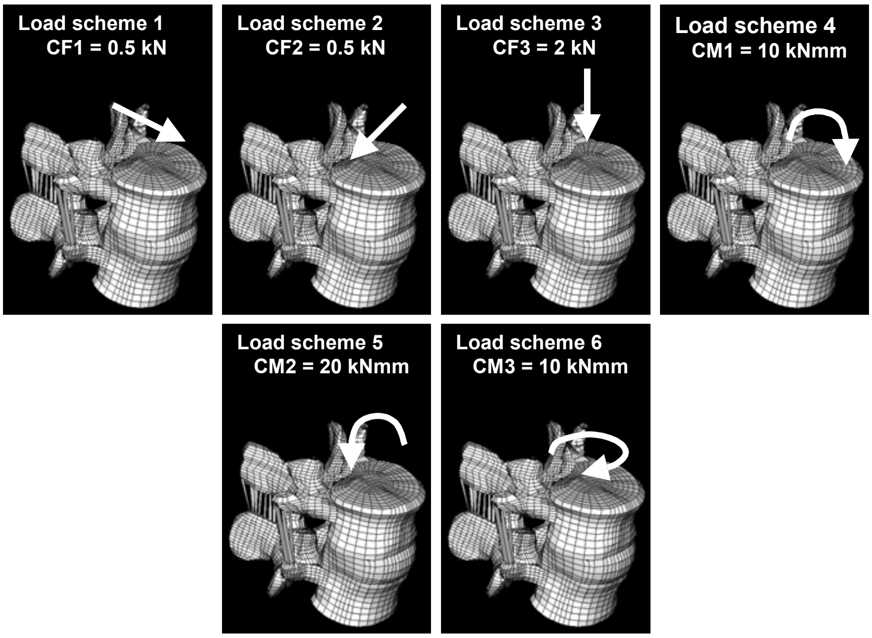

Fig. 3. Six schemes of loading applied to motion segment model

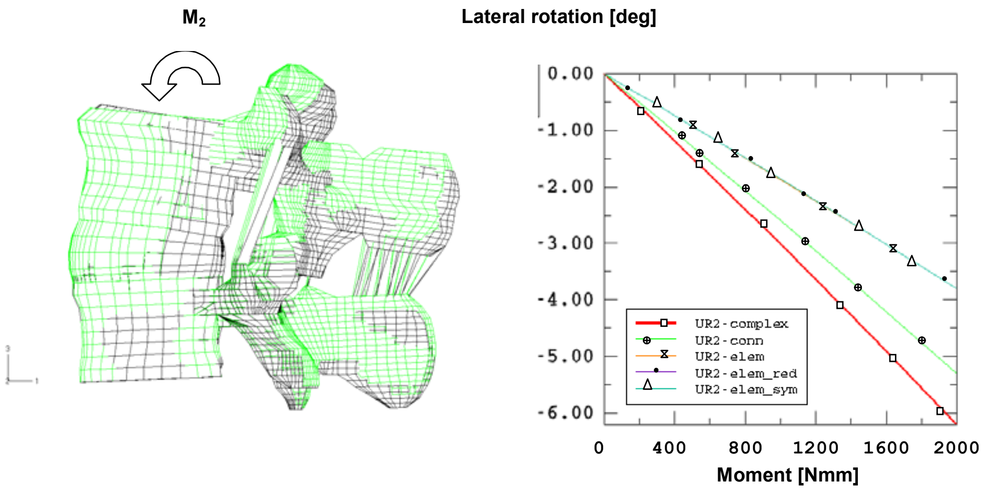

Fig. 4. Load case 4 – bending moment M_2 = 2000 Nmm

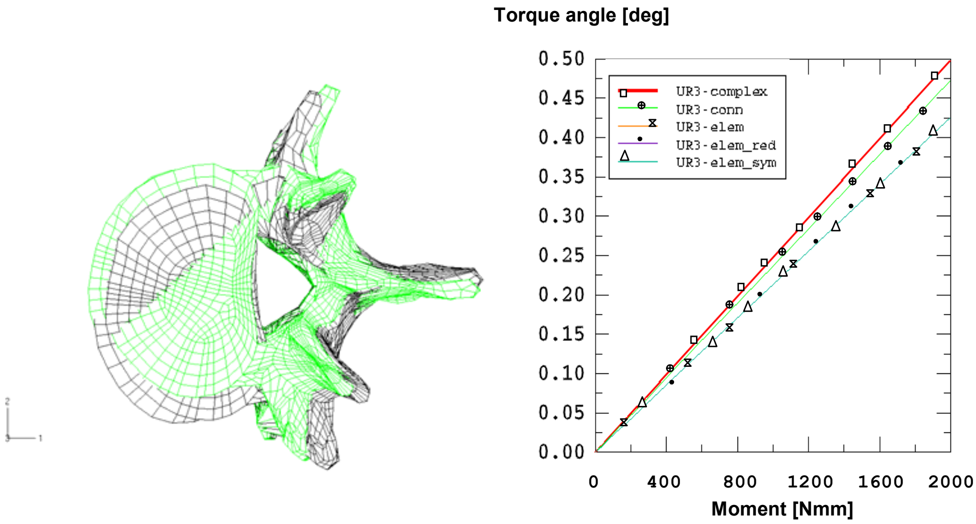

Fig. 5. Load case 6 – torsional moment M_t = 2000 Nmm

In figures 4 and 5, some selected results of validation of disc simplification concepts of complete motion segment model are presented (lateral and torsional bending).

On the basis of the results obtained it was possible to verify the validity and quality of the model definition. The axial displacement and disc bulge for compression, and rotation for bending and an axial rotation for torsion were compared to the values taken from literature [9], [18] and their agreement was satisfactory. The bulging of the disc as well as its structured behaviour are easily noticed. The results obtained for models that used one element with different formulations (with full, symmetrized and reduced matrices) did not practically differ. However, this approach is not firm enough in comparison with the application of connector-type elements. The linear response within the examined range of deformations is evident, so the load independence of the stiffness coefficients has been approved taking into account the fact that the stiffness matrix does not possess the symmetry properties.

5. Conclusions

This paper was focused on the intervertebral disc modelling to obtain its integrated properties and finally to replace it by a simple 6 dof element. Two different ways of disc modelling were proposed. Both allow us to arrive at the similar results, however the application of the rebar layers embedded in 3D solid elements seems to be more convenient when considering any type of model modification or parametric studies. The concept of disc simplification by means of 2-node element with 12 × 12 stiffness matrix is promising, however it depends on coordinate system.

The presented approach to the replacement of the intervertebral disc by a connector-type element is satisfying enough and makes the analysis of human lumbar spinal segment much simpler. This concept may be applied further in surgery simulations, analyses of spinal equilibrium and stability. The next step is to apply this approach to hierarchical modelling of the whole human spine.

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References

[1] ADAMS M.A., BOGDUK N., BURTON K., DOLAN P., *The Biomechanics of Back Pain*, Elsevier Science Limited, Churchill Livingstone, 2002.

[2] BĘDZIŃSKI R., *Biomechanika inżynierska*, Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław, 1997.

[3] DIETRICH M., KĘDZIOR K., WITTEK A., ZAGRAJEK T., *Non-Linear Finite Element Analysis of Formation and Treatment of Intervertebral Disc Herniae*, Proc. Inst. Mech. Eng., 1992, pp. 225–31.

[4] EBERLEIN R., HOLZAPFEL G.A., SCHULZE-BAUER C.A.J., *Assessment of a Spinal Implant by Means of Advanced FE Modeling of Intact Human Intervertebral Discs*, Fifth World Congress on Computational Mechanics, Vienna, 2002.

[5] GOEL V.K., KIMY E., LIM T.H., *An analytical investigation of the mechanics of spinal instrumentation*, Spine, 1988, 13, pp. 1003–1011.

[6] KĄKOL W., ŁODYGOWSKI, T., OGURKOWSKA M.B., WIERSZYCKI M., *Are we able to support medical diagnosis or rehabilitation of human vertebrea by numerical simulation?* 15th Int. Conf. on Computer Methods in Mechanics, June 3–6, 2003, Gliwice, Poland.
[7] KIM Y.E., CHO S.Y., CHOI H.Y., *Analysis of Dural-SAC Occlusion in a Lumbar Spinal Motion Segment FE Model*, Journal of Musculoskeletal Research, 2001, Vol. 5, No. 4, pp. 243–252.
[8] LIM T.-H., GOEL V.K., WEINSTEIN J.N., *Stress Analysis of a Canine Spinal Motion Segment Using the Finite Element Technique*, J. Biomech., 1994, Vol. 27, pp. 1259–1269.
[9] LU Y.M., HUTTON W.C., GHARPURAY V.M., *Can Variations in Intervertebral Disc Height Affect the Mechanical Function of the Disc?* Spine, 1996, Vol. 21, No. 19, pp. 2208–2217.
[10] NEIL J.L., DEMOS T.C., *Tensile and Compressive Properties of Vertebral Trabecular Bone*, Trans. 29 th Orthop. Res. Soc., 1983, 8, pp. 344.
[11] OGURKOWSKA M.B., *Application of radiology and rheology method for mechanical testing of the vertebral column*, PhD Thesis, University School of Physical Education, Poznań, 1992.
[12] OGURKOWSKA M.B., *Variation of the vertebral body strength with sampling position in a vertebral body for L1–L5*, Journal of Biomechanics (submitted for publication).
[13] OGURKOWSKA M.B., RYCHLIK M., STANKIEWICZ W., NOWAK M., ROSZAK R., GLEMA A., WIERSZYCKI M., MORZYŃSKI M., ŁODYGOWSKI T., *The interaction of the L4–L5 spinal segments by FEM analysis.* Part 1. *Methods of geometrical data acquisition and validation*, Acta of Bioengineering and Biomechanics, 13th Conference of the European Society of Biomechanics, 2002, Vol. 4, Supp. 1, Wrocław, Poland, pp. 98–99.
[14] OGURKOWSKA M.B., RYCHLIK M., STANKIEWICZ W., NOWAK M., ROSZAK R., GLEMA A., WIERSZYCKI M., MORZYŃSKI M., ŁODYGOWSKI T., *The interaction of the L4–L5 spinal segments by FEM analysis.* Part 2. *Virtual modeling of the structure*, Acta of Bioengineering and Biomechanics, 13th Conference of the European Society of Biomechanics, 2002, Vol. 4, Supp. 1, Wrocław, Poland, pp. 98–99.
[15] RAO A.A., DUMAS G.A., *Influence of Materials Properties on the Mechanical Behavior of the L5–S1 Intervertebral Disc in Compression: A Nonlinear Finite Element Study*, J. Biomed. Eng., 1991, Vol. 13, pp. 139–151.
[16] RYCHLIK M., MORZYŃSKI M., NOWAK M., STANKIEWICZ W., ŁODYGOWSKI T., OGURKOWSKA M., *Acquisition and transformation of biomedical objects to CAD systems*, Strojnicky Casopis, 2004, Vol. 55, No. 3, Bratislava, pp. 121–135.
[17] SKAGGS D.L., WEIDENBAUM M., *Regional variation in tensile properties and biomechanics composition of the human lumbar annulus fibrous*, Spine, 1994, Vol. 9, pp. 120–134.
[18] SKIRAZE-ADL A. et al., *Stress analysis of the lumbar disc-body unit in compression: a three-dimensional nonlinear finite element study*, Spine, 1984, Vol. 9, pp. 120–134.
[19] STANKIEWICZ W., ROSZAK R., *Generation of the CAD models based on NMR measurements of human tissues* (in Polish), Zeszyty Naukowe Politechniki Poznańskiej, 2001, No. 53, pp. 47–52.
[20] SUWITO W., KELLER T.S., *Geometric and material property study of the human lumbar spine using the finite element method*, J. Spinal Disord., 1992, Vol. 5, pp. 50–59.
[21] SWATRZ D.E., WITTENBERG R.H., *Physical and mechanical properties of calf lumbosacral trabecular bone*, J. Biomechanics, 1991, Vol. 24, No. 11, pp. 1059–1068.
[22] TEO E.C., NG H.E., *Evaluation of the role of ligaments, facets and disc nucleus in lower cervical spine under compression and sagittal moments using finite element method*, Medical Engineering & Physics, 2001, Vol. 23, pp. 155–164; Elsevier Science Ltd.
[23] ZIENKIEWICZ O.C., TAYLOR R.L., *The Finite Element Method*, Butterwoth Heinemann, Oxford, 2000.