An ACA/BEM for solving wave propagation problems in non - homogeneous materials.

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ABSTRACT: The present work reports a study on the propagation of elastic waves in unidirectional fiber reinforced composite materials. The fiber composite is modeled as a slab consisting of a large number of randomly or uniformly distributed elastic fibers embedded in an elastic matrix medium. That slab is also embedded in an infinitely extended matrix material, where a longitudinal plane wave propagates and impinges upon the considered composite material. The goal of the present work is twofold: first to solve numerically the just described large-scale scattering problem and second to compare the obtained results with those taken by the solution of the same problem with the composite material being homogenized according to an Iterative Effective Medium Approximation (IEMA) [J. Acoust. Soc. Am. 116, 3443–3452 (2004)]. To this goal an advanced Boundary Element Method (BEM) effectively combined with an Adaptive Cross Approximation (ACA) algorithm is employed. For very high number of inclusions, the proposed ACA/BEM technique solves the considered large-scale scattering problem with memory requirements of almost linear complexity.

1 INTRODUCTION

The propagation of a plane wave in particulate and fiber composites is always characterized by dispersion and attenuation due to its multiple scattering by the embedded in-homogeneities. Thus, even in the case where the constituents of the composite are non-dispersive and non-attenuative materials, any elastic wave propagating in the main body of the composite undergoes both dispersion and attenuation. A methodology of estimating the dispersive and attenuative properties of a composite elastic medium is that of Iterative Effective Medium Approximation (IEMA) proposed by Tsinopoulos et al. (2000), Verbis et al. (2001) and Aggelis et al. (2004). The IEMA makes use of the single inclusion self-consistent condition of Kim et al. (1995) and assumes that the effective stiffness of the composite is the same with the corresponding static one and evaluates iteratively the effective and frequency dependent dynamic density of the composite. The complex value of the effective dynamic density and the static effective stiffness of the composite determine, eventually, the wave speed and the attenuation coefficient of the plane wave propagating through the composite material.

The goal of the present work is to check numerically the validity of IEMA by comparing the results of two main problems. The first problem considers a slab of a large number of randomly distributed elastic fibers embedded in an infinitely extended elastic matrix medium where a longitudinal plane wave propagates and impinges perpendicularly upon the fibers. In the second problem a homogeneous material with frequency dependent properties evaluated by the IEMA replaces the slab of fibers. In both problems the elastic energy scattered in the forward direction is evaluated by the Boundary Element Method (BEM) and the obtained results are compared to each other.

The Boundary Element Method (BEM) is a very well known and robust numerical tool successfully used for the solution of wave scattering problems. Two remarkable advantages it offers as compared to other numerical methods is the reduction of the dimensionality of the problem by one and its high solution accuracy. Despite the advantages the brutal application of BEM to large-scale problems, like that of scattering by a large number of fibers, suffers from very time consuming computations and high demands for computer memory capacity. Both problems come from the generation of the non-symmetric coefficient matrix $[\mathbf{A}]$ and the solution of the final system of algebraic equation $[\mathbf{A}]\cdot\{\mathbf{x}\}=\{\mathbf{b}\}$. More precisely, the fully populated matrices produced by BEM require $O(N^2)$ operations for its buildup and O(N^3) operations for the solution of the final matrix system through Gaussian elimination or typical LU-decomposition solvers. The use of iterative solvers decreases the operation requirements from O(N^3) to O(MxN^2), with M being the number of iterations, but still remains inefficient for large scale problems. To the same conclusion we reach when parallel computing methods are exploited for the solution of the problem.

An alternative approach to accelerate BEM is the recently proposed adaptive cross approximation algorithm (ACA) along with hierarchical matrices (Bebendorf and Rjasanow (2003), Borm *et al.* (2003), Brunner *et al.* (2010)). The acceleration here, is achieved because only a small number of elements of the collocation matrix $[\mathbf{A}]$ are calculated, while the rest ones are approximated via the already calculated values. In the present work an advanced ACA/BEM efficiently combined with iterative solvers, proposed by Gortsas *et al.* (2015)), is employed for the solution of the aforementioned scattering problems. That ACA/BEM technique is explained in brief in the next section while the IEMA is illustrated in the section after next. Finally, the obtained results are reported and discussed in the forth section.

2 SOLUTION OF SCATTERING PROBLEM VIA ACA/BEM

Consider q identical, circular elastic fibers of radius a, density ρ_f, Young modulus E_f and Poisson ratio ν_f embedded in an infinitely extended elastic matrix with material properties ρ_m, E_m and ν_m respectively. A harmonic longitudinal plane wave propagating in $\hat{\mathbf{k}}$ direction with frequency ω impinges upon the cloud of randomly or uniformly distributed elastic fibers (Fig. 1).

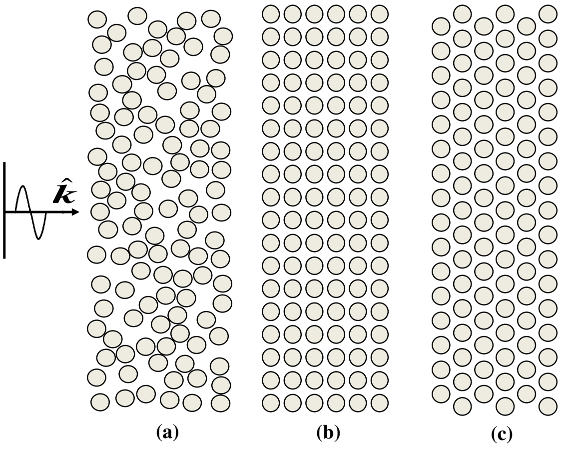

Figure 1. A longitudinal plane wave propagating in $\hat{\mathbf{k}}$ direction impinges upon the q (a) randomly, (b) square and (c) hexagonal distributed elastic fibers

The just described two-dimensional (2D) elastostodynamic problem admits an integral representation of the form:

$$\frac{1}{2}\mathbf{u}^{(m)}(\mathbf{x})+\int_S \tilde{\mathbf{t}}^*(\mathbf{x},\mathbf{y},\omega)\cdot\mathbf{u}^{(m)}(\mathbf{y})\,dS_{\mathrm{y}}= \int_S \tilde{\mathbf{u}}^*(\mathbf{x},\mathbf{y},\omega)\cdot\mathbf{t}^{(m)}(\mathbf{y})\,dS_{\mathrm{y}}+\mathbf{u}^{inc}(\mathbf{x}) \tag{1}$$

$$\frac{1}{2}\mathbf{u}^{(f)}(\mathbf{x})+\int_{S_i} \tilde{\mathbf{t}}^*(\mathbf{x},\mathbf{y},\omega)\cdot\mathbf{u}^{(f)}(\mathbf{y})\,dS_{\mathrm{y}}= \int_{S_i} \tilde{\mathbf{u}}^*(\mathbf{x},\mathbf{y},\omega)\cdot\mathbf{t}^{(f)}(\mathbf{y})\,dS_{\mathrm{y}},\ i=1,2,...,q \tag{2}$$

where S_i is the boundary of each fiber, $S=S_1+\ldots+S_q$, $\mathbf{x}$ and $\mathbf{y}$ are points at S_i, $\mathbf{u}$ and $\mathbf{t}$ are the displacement and traction vector, respectively, the superscripts (f) and (m) indicate fiber and matrix, respectively and $\tilde{\mathbf{u}}^*(\mathbf{x},\mathrm{y},\omega)$ and $\tilde{\mathbf{t}}^*(\mathbf{x},\mathrm{y},\omega)$ are the 2D free space frequency domain elastodynamic fundamental displacement and traction tensor, respectively, explicitly given in Polyzos *et al.* (1998).

According to a conventional BEM formulation, the boundaries S_i are discretized into three-noded quadratic line elements with the general rule of using four elements per wave length of the incident wave. Collocating Eqs. (1) and (2) at all nodes and applying the continuity boundary conditions valid for displacements ant tractions at all fiber surfaces, one obtains a system of algebraic equations written in matrix form as

$$[\mathbf{H}]\cdot\{\mathbf{u}\}=[\mathbf{G}]\cdot\{\mathbf{t}\}+\{\mathbf{u}^{inc}\} \tag{3}$$

where the matrices [**G**] and [**H**] contain evaluated integrals having kernels corresponding to fundamental displacement and traction, respectively, the components of vectors {**u**} and {**t**} comprises all the nodal displacements and tractions, respectively and the vector {$\mathbf{u}^{\mathrm{inc}}$} contains all the known values of the incident wave at each node of the discretized surfaces.

Rearranging Eq. (3) and keeping only the known vectors at the right hand side, one obtains the final linear system of algebraic equations

$$[\mathbf{A}]\cdot\{\mathbf{x}\}=\{\mathbf{u}^{inc}\} \tag{4}$$

As it has been already mentioned in the introduction, in conventional BEM, $[\mathbf{A}]$ is a full populated matrix requiring O(N^2) operations for its buildup and O(N^3) operations for the solution of Eq. (4) via Gaussian elimination or typical LU-decomposition solvers, which is prohibitive for solving realistic problems where the degrees of freedom N are of the order of hundreds of thousands. In order to overcome the conventional BEM memory limitations and solve the above described problem for a large number of fibers, a hierarchical ACA accelerated BEM is proposed. More precisely, the matrices $[\mathbf{H}]$ and $[\mathbf{G}]$ appearing in Eq. (3), are represented hierarchically using a block tree structure. By means of simple geometric considerations the blocks, which correspond to large distances between source and collocation points, are characterized as far field blocks (or admissible) and compressed using low rank matrices found by an ACA algorithm (Bebendorf and Rjasanow (2003), Borm *et al.* (2003), Brunner *et al.* (2010)). The rest blocks of the tree, which are dominated by the singular behavior of the fundamental displacement and traction kernels, are characterized as near field blocks (or non-admissible) and are fully calculated as in conventional BEM. Furthermore, a significant reduction of the solution time of the problem is accomplished by utilizing the iterative solver GMRES for the solution of Eq. (4). According to that solver, the matrix $[\mathbf{A}]$ is never formed explicitly, saving significant amount of memory which corresponds to the zero values appearing in $[\mathbf{A}]$ due to the fact that $[\mathbf{G}]$ and $[\mathbf{H}]$ are uncoupled between each other. Thus, the GMRES multiplications are performed directly in Eq. (3) and a block left diagonal preconditioner is used to accelerate the convergence. The block dimensions are chosen to be approximately equal to the number of nodes that each fiber is discretized into and the block's inversion is performed using the LU decomposition algorithm. More details on the aforementioned ACA/BEM technique can be found in Gortsas et al. (2015).

3. THE ITERATIVE EFFECTIVE MEDIUM APPROXIMATION (IEMA)

In this section the main steps of IEMA are illustrated. When a plane wave propagates in a nonhomogeneous medium, it can be considered as a sum of a mean wave travelling in the medium with the dynamic effective properties of the composite and fluctuating waves derived from the multiple scattering of the mean wave. The basic idea of IEMA is that the fluctuating waves should be vanished at any direction within the effective medium. That hypothesis is reflected by the relation (Kim et al. (1995)):

$$n_1 g_d^{(1)}(\hat{\boldsymbol{d}};\hat{\boldsymbol{k}},\hat{\boldsymbol{k}}) + n_2 g_d^{(2)}(\hat{\boldsymbol{d}};\hat{\boldsymbol{k}},\hat{\boldsymbol{k}}) = 0 \tag{5}$$

where n_1, n_2 represent the volume concentration of fibers and matrix medium, respectively, with $n_1+n_2=1$, $\hat{\boldsymbol{k}}$ is the direction of wave propagation, $\hat{\boldsymbol{d}}$ is the polarization vector of incident wave and $g_d^{(1)}, g_d^{(2)}$ are the forward scattering amplitudes derived from the solution of two single-scatterer problems, i.e. the scattering of a longitudinal (d=P) or transverse (d=S) wave by an inclusion and matrix fiber, respectively, embedded in a material having the effective properties of the composite.

The mean wave is both dispersive and attenuated and has a complex wavenumber $k_d^{eff}(\omega)$ defined as:

$$k_d^{eff}(\omega) = \frac{\omega}{C_d^{eff}(\omega)} + i\alpha_d^{eff}(\omega), \tag{6}$$

where $C_d^{eff}(\omega), \alpha_d^{eff}(\omega)$ stand for the effective and frequency dependent phase velocity and attenuation coefficient, respectively of a mean wave propagating with circular frequency ω. In order to determine both $C_d^{eff}(\omega), \alpha_d^{eff}(\omega)$, the IEMA proposes the following iterative procedure:

First, the composite medium is replaced by an elastic homogeneous and isotropic medium with material properties E^{eff} and ν^{eff}, calculated by using the static mixture model of Christensen (1990).

The effective density of the nonhomogeneous medium has been taken equal to

$$(\rho^{eff})_{step1} = n_1\rho_1 + n_2\rho_2 \tag{7}$$

In the first step of the iteration procedure, the real effective wave number $(k_d^{eff})_{step1}$ of the mean wave can be calculated by the well-known equations valid for longitudinal and shear waves, respectively:

$$(k_p^{eff})_{step1} = \omega\sqrt{\frac{(\rho^{eff})_{step1}}{E^{eff}}\frac{\left(1+\nu^{eff}\right)\left(1-2\nu^{eff}\right)}{\left(1-\nu^{eff}\right)}}$$

$$(k_s^{eff})_{step1} = \omega\sqrt{\frac{(\rho^{eff})_{step1}}{E^{eff}}2\left(1+\nu^{eff}\right)} \tag{8}$$

Next, utilizing $E^{eff}, \nu^{eff}, (k_d^{eff})_{step1}$, the forward scattering amplitudes $g_d^{(1)}, g_d^{(2)}$ are evaluated and the validity of the self-consistent relation (5) is checked. If it is not true, then we proceed to the second step where the dispersion relation proposed by Foldy (1945) is exploited for the evaluation of wavenumbers of second step, i.e.

$$(k_d^{eff})_{step2} = (k_d^{eff})_{step1} + \frac{3n_1 g_d^{step1}(\hat{\boldsymbol{d}};\hat{\boldsymbol{k}},\hat{\boldsymbol{k}})}{a^2 (k_d^{eff})_{step1}} \tag{9}$$

with a being the radius of the fiber and

$$g_d^{step1} = [n_1 g_d^{(1)} + n_2 g_d^{(2)}]^{step1} \tag{10}$$

The procedure is continued until the self-consistent Eq. (5) to be satisfied. If l is the final step, the phase velocity $C_d^{eff}(\omega)$ and the attenuation coefficient $\alpha_d^{eff}(\omega)$ are evaluated from the relation

$$\left(k_d^{eff}(\omega)\right)_{stepl} = \frac{\omega}{C_d^{eff}(\omega)} + i\alpha_d^{eff}(\omega), \tag{11}$$

More details can be found in Aggelis et al. (2004) and Verbis et al. (2001).

4. NUMERICAL RESULTS

In Fig. 2 the magnitude of radial scattering amplitudes in the forward direction, for three different fiber arrangements (Fig. 1) are presented for a propagating longitudinal wave, with respect to the range of non-dimensional frequencies $ka = 0.1 - 2$. The size of the virtual control volume containing the fibers for all three cases is $180x540\mu m$. The volume fraction is 35% for the square and random fiber arrangement and 32% for the hexagonal arrangement. The total number of the considered identical fibers is 108 for the square and random arrangements and 99 for the hexagonal, while their radius is $a = 10\mu m$. The material properties used are presented in Table 1.

Table 1. Material properties for the fibers and the matrix.

Material	ρ (kg/m$^{3)}$	E (GPa)	v
Aluminum AA520 (matrix)	2600	66	0.31
Alumina Al_2O_3 (fibers)	3700	360	0.25

Similarly, in Fig. 3 the magnitude of the vertical scattering amplitudes in the forward direction, for a propagating shear wave, are presented for the three different arrangements and the same non-dimensional frequency range.

In both cases, the results obtained for the three different fiber arrangements are compared to the corresponding ones taken when fibers and surrounding material is replaced by a homogeneous slab with frequency dependent properties provided by IEMA for the same frequency range.

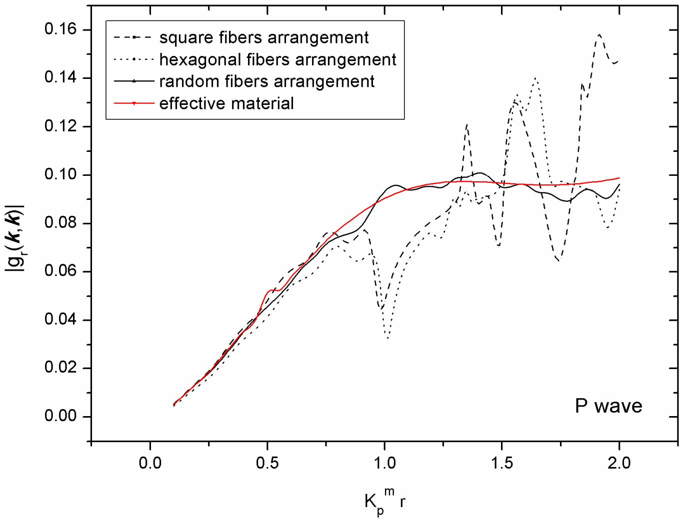

Figure 2. Radial scattering amplitude in the forward direction for a propagating longitudinal wave, calculated for the square, random and hexagonal fiber arrangements, as well as the effective material provided by IEMA.

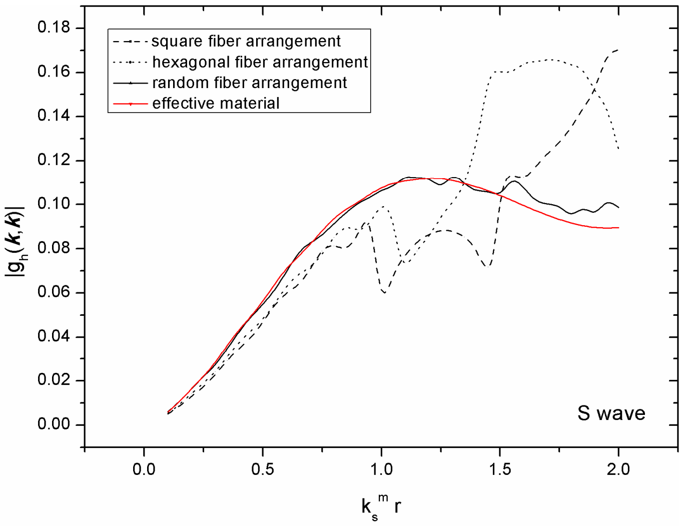

Figure 3. Horizontal scattering amplitude in the forward direction for a propagating longitudinal wave, calculated for the square, random and hexagonal fiber arrangements, as well as the effective material provided by IEMA.

Observing Figs 2 and 3 one can say that the results obtained for the effective material provided by IEMA are in very good agreement with the corresponding ones taken by the random arrangement of fibers at all the considered frequencies. For low frequencies (k*a*<1) the same conclusion is valid for the periodic arrangements of fibers. For dimensionless frequencies k*a*>1 there are significant differences between the periodic and the random arrangement of fibers. In the case of periodic arrangement of fibers there are certain frequencies where a sudden decrease of the value of the scattering amplitude is observed. For those frequencies part of the scattered energy is either diverted in different directions than the forward one or it is trapped between the scatterers as standing waves. Moreover there are also frequencies where the scattered energy in the forward direction is amplified due to the multiple scattering effect.

Finally, in order to examine the prediction capability of IEMA in other directions than the forward one, the magnitude of the radial scattering amplitude is calculated for a longitudinal incidence in randomly distributed fibers and for three different frequencies *ka*=0.1,1,2 at the angle range 0^0-180^0, with the angles 0^0 and 180^0 representing the forward and backward direction, respectively. The obtained results are depicted in Figs 4,5 and 6 and as it is observed IEMA predicts pretty well the scattered energy by the composite with the random arrangement of fibers at all directions, while provides almost identical results for the angle range 0^0-20^0.

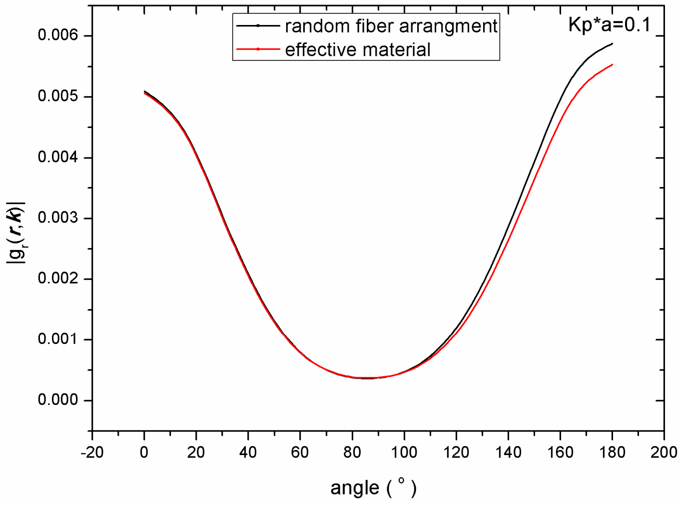

Figure 4. Magnitude of the radial scattering amplitude for different angles and frequency k*a=0.1.

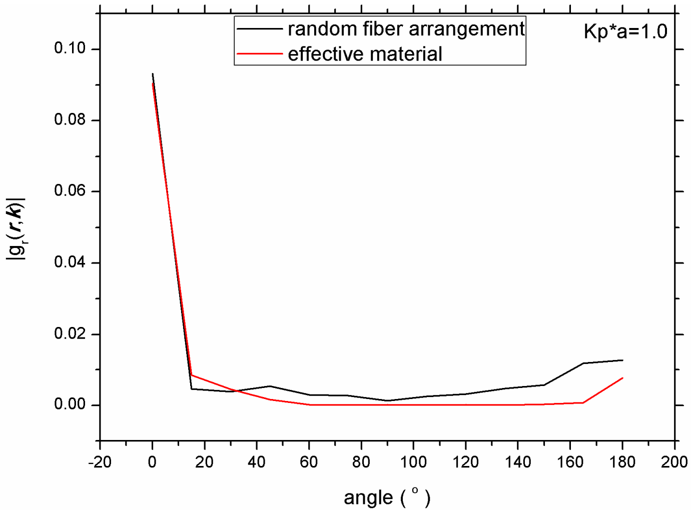

Figure 5. Magnitude of the radial scattering amplitude for different angles and frequency k*a=1.0.

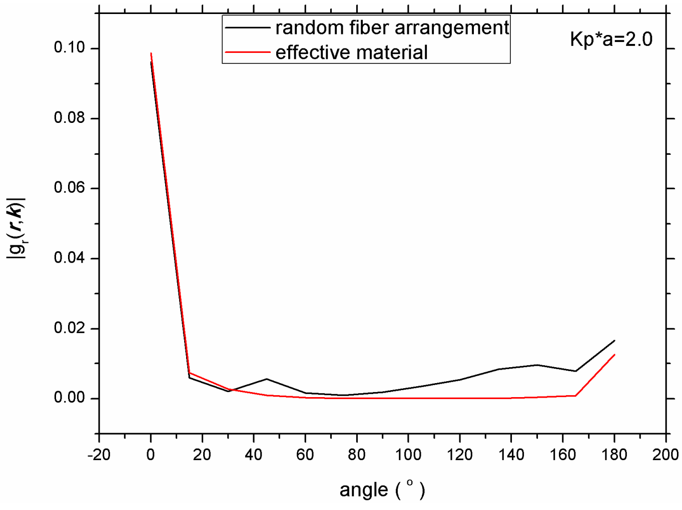

Figure 6. Magnitude of the radial scattering amplitude for different angles and frequency k*a=2.0.

5. CONCLUSIONS

The propagation of longitudinal and shear elastic waves in unidirectional fiber reinforced composite slabs has been studied for three different arrangements of fibers (random, square and hexagonal). The corresponding problems have been solved with the aid of an advanced ACA/BEM and the obtained results have been compared to the corresponding ones taken after the homogenization of the composite through the IEMA. The main conclusions are: (a) for propagation in the forward direction and for low frequencies IEMA works well for all the arrangements of fibers, (b) for high frequencies IEMA supports effectively the wave propagation only in the composite with the random distribution of the fibers and (c) IEMA predicts pretty well the scattered energy by the composite with the random arrangement of fibers at almost all directions.

ACKNOWLEDGEMENT

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Day 0
Tuesday 26/5/2015

17:00-19:00	Pre-registration and welcome in MEMC VUB, Building Kb

Day 1
Wednesday 27/5/2015

8:30	Opening ceremony
9:00	**Plenary talk, Neutron techniques for NDT, *Helena Van Swygenhoven-Moens (room Q.D)***

	Room Q.B	Room Q.D	Room Q.C
	Application of NDT/SHM techniques to cultural heritage 1 **Chairs: Prof. A. Saisi, Prof. A. Moropoulou**	**Optical sensors for structural health monitoring** **Chair: Prof. Steve Vanlanduit**	**NDT in aerospace** **Chair: Dr. Helge Pfeiffer**
9:50	Methodology of non-destructive testing in scientific support to decision making for the compatible and sustainable protection of Cultural Heritage, *A. Moropoulou* **(keynote)**	SMARTFIBER: miniaturized optical-fiber sensor based health monitoring system, *N. Lammens, G. Luyckx, E. Voet, W. Van Paepegem, J. Degrieck* ***(Keynote)***	Fuse-like devices replacing linear sensors - working examples of percolation sensors in operational airliners and chemical installations, *H. Pfeiffer, H. Sekler, M. Schoonakker, M. Wevers* ***(Keynote)***
10:20	Efficiency of ND techniques for structural assessment and seismic damage detection of historical masonry through integration and data fusion, *V. Z. Bosiljkov, P. Cotič, Z. Jagličić*	Combining Embedded Fibre Bragg Grating Sensors and Modal Analysis techniques to monitor fatigue induced propagating delamination in composite laminates, *Alfredo Lamberti, Gabriele Chiesura, Ben De Pauw, Steve Vanlanduit*	Lamb wave dispersion time-domain study using a combined signal processing approach, *Pedro Ochôa, Roger M. Groves, Rinze Benedictus*
10:40	Surface damage determination at a Jewish grave, found in front of the central building of Aristotle University of Thessaloniki, using two different “ultrasonic velocity” methods. *B. Christaras, A. Moropoulou, M. Chatziangelou, L. Dimitraki & C. Devlioti*	The novel potential for embedded strain measurements offered by microstructured optical fiber Bragg gratings, *T. Geernaert, S. Sulejmani, C. Sonnenfeld, G. Luyckx, J. Degrieck, D. Van Hemelrijck, H. Thienpont, and F. Berghmans*	Thermal strains in heated fibre metal laminates, *B. Müller, A. G. Anisimov, R. M. Groves, J. Sinke*
11:00	Coffee break (Q, room Nelson Mandela)		

	Application of NDT/SHM techniques to cultural heritage 2 **Chairs: Prof. A. Saisi, Prof. A. Moropoulou**	**Elastic waves 1 (with emphasis on enhanced theories)** **Chair: Prof. Polyzos**	**Applications 1** **Chair: Prof. Els Verstrynge**
11:10	Tube-Jack and Sonic Testing for the Evaluation of the State of Stress in Historical Masonry, *E.C. Manning, L.F. Ramos, F.M. Fernandes, P.B. Lourenço*	Modelling the dispersive behavior of fresh and hardened concrete specimens through non-local lattice models, *S. N. Iliopoulos, D. Polyzos, D. G. Aggelis*	Non-destructive Evaluation of an Infusion Process using Capacitive Sensing Technique, *Yang Yang, Gabriele Chiesura, Thomas Vervust, Frederick Bossuyt, Geert Luyckx, Markus Kaufmann, Joris Degrieck, Jan Vanfleteren*
11:30	Optical and laser scanning techniques for monitoring damages on historic buildings and artifacts, *C. Ioannidis*	An ACA/BEM for solving wave propagation problems in non-homogeneous materials, *T. Gortsas, I. Diakides, D. Polyzos*	In-situ testing using combined NDT methods for the technical evaluation of existing bridge, *N. V. Zoidis, E. N. Tatsis, T. E. Matikas*
11:50	Traditional and innovative strain sensing techniques in the study of the mechanical response of marble structural elements, *S. K. Kourkoulis, D. Triantis, I. Stavrakas, G. Hloupis and E. D. Pasiou*	Strain gradient elastic theory in non destructive testing, S. N. Iliopoulos, D. Polyzos, D. G. Aggelis	Assessment of eSHM system combining different NDT methods, *M. Strantza, D. G. Aggelis, D. De Baere, M. Hinderdael, P. Guillaume, D. Van Hemelrijck*
12:10	Health monitoring of post-Byzantine monuments by IR thermography, *D.A. Exarchos, E.Z. Kordatos, C. Stavrakos, A.I. Moropoulou, T.E. Matikas*	Surface Residual Stress Using Sound Wave Velocity Variation, *S.Kumar, M.J.Tan, B.S.Wong, N.Weeks*	Assessment of grouted connection in monopile wind turbine foundations using combined non-destructive techniques, *A. N. Iliopoulos, C. Devriendt, D. Van Hemelrijck, D. G. Aggelis*
12:30	Lunch		
	Application of NDT/SHM techniques to cultural heritage 3 **Chairs: Prof. A. Saisi, Prof. A. Moropoulou**	**Elastic wave methods 2** **Chair: Prof. K. Van Den Abeele**	**Combination of NDT techniques 1** **Chair: T.E. Matikas**
13:40	Documentation of the structural system of historic structures assisted by radar and boroscope, *Elizabeth Vintzileou*	The Ultrasonic Polar Scan: Past, Present and Future, M. Kersemans, A. Martens, S. Delrue, K. Van Den Abeele, L. Pyl, F. Zastavnik, H. Sol, J. Degrieck and W. Van Paepegem	A condition monitoring methodology for tidal turbines combining acoustic emission and vibration analysis, *Juan Luis Ferrando Chacon, Jesus Antonio Jimenez, Antonio Romero, Vassilios Kappatos, Cem Selcuk, Slim Soua and Tat-Hean Gan*

14:00	Detection and localization of debonding damage in composite-masonry strengthening systems with the acoustic emission technique, *E. Verstrynge, B. Ghiassi, M. Wevers, K. Van Balen, D.V. Oliveira*	Ultrasonic Testing of Adhesively Bonded Joints in Glass Panels, *B. Mojškerc, T. Kek, J. Grum*	Concrete Compressive Strength Estimation by means of Combined NDT, *G. Concu, B. De Nicolo, N. Trulli, M. Valdés*
14:20	Comprehensive diagnosis methodology integrating NDT, energy performance simulation and monitoring techniques for energy efficient historic buildings refurbishment, *M. A. García-Fuentes, J. L. Hernández, C. Colla, A. Meiss*	Guided ultrasonic waves for the NDT of immersed plates, *P.Rizzo, E. Pistone, A. Bagheri*	Construction and Characterization of 3-D Phononic structures by Non-Destructive Techniques, *D. A. Exarchos, I. K. Tragazikis, P. T. Dalla, I. E. Psarobas, T. E. Matikas*
14:40	Dynamic Investigation of the Ties-rods of the Milan Cathedral, *C. Gentile, M. Guidobaldi, C. Poggi, M. Vasic*	Ultrasonic NDT of prefabricated titanium-composite joints, *V.Samaitis, E. Jasiūnienė, L.Mažeika, D.Mattsson*	Detection of incipicient SCC damage in primary loop piping using acoustic emission & fibre optic strain gages, *Benjamin K. Jackson, Dr. Jonnathan L. W. Warwick, James J. Wall*
15:00	Numerical methods for the interpretation and exploitation of AE monitoring results, *S. Invernizzi, G. Lacidogna, A. Carpinteri*	Development of an advanced Phased Array Ultrasonic technique for the assessment of aerospace composite structures - From modelling predictions to experimental results, *Cheilakou, P. Theodorakeas, I. Hatziioannidis, R. Marini, M. Koui*	Comparative study of NDT inspection methods in Carbon Fiber Composite Laminates, *G. Steenackers, J. Peeters, G. Arroud, S. Wille*
15:20	Non-destructive Testing and Finite Element Modeling of a Modern Heritage Bridge, *C. Gentile, A. Saisi*	Heavy Wall Pipe Line Inspection by Phased Array Ultrasonic Test (PAUT) and Comparison with Conventional NDT Methods, *A. Yousefi, M. Esmaeilian, D. Ghasemi*	Use of 4D µCT to measure changes of morphological properties and local deformation of materials across a temperature gradient, *Nicholas Lippiatt, Grzegorz Pyka and Martine Wevers*
15:40	Coffee break (Q, room Nelson Mandela)		
	Application of NDT/SHM techniques to cultural heritage 4 **Chairs: Prof. A. Saisi, Prof. A. Moropoulou**	**Elastic waves 3 (with emphasis in nonlinearity)** **Chair: M .Bentahar**	**Applications 2 (Self healing and thermal methods)** **Chair: N.J. Siakavelas**
15:50	On site investigation and continuous dynamic monitoring of a historic Tower in Mantua, Italy, *A. Saisi, M. Guidobaldi, C. Gentile* ***(Keynote)***	Nonlinear Acoustics and Acoustic Emission Methods to Monitor Damage in Mesoscopic Elastic Materials, *M. Bentahar, R. El Guerjouma, C. Mechri, Y. Baccouche, A. Novak, S. Toumi, V. Tournat, L. Simon, S. Idjimarene, M. Scalerandi* ***(Keynote)***	Non-destructive testing techniques to evaluate the healing efficiency of self-healing concrete at lab-scale, *E. Gruyaert, J. Feiteira, F. Malm, E. Tziviloglou, E. Schlangen, C.U. Grosse, N. De Belie* ***(Keynote)***

16:20	Raman Spectroscopy. A Non-destructive Tool for on-site Chemical Analysis of Artifacts and Monuments, *E. Kamilari, C. Kontoyannis*	A Simulation Study of Local Defect Resonances (LDR), *S. Delrue, K. Van Den Abeele*	Non-contact photothermal characterization of thermophysical properties by using fluorescence based thermometry, *Liwang Liu, Kuo Zhong, and Christ Glorieux*
16:40	Novel applications of micro-destructive cutting techniques in cultural heritage, *M. Theodoridou, I. Ioannou*	Time-of-Flight Recorded Pulsed Ultrasonic Polar Scan for Elasticity Characterization of Composites, *M. Kersemans, A. Martens, S. Delrue, K. Van Den Abeele, L. Pyl, F. Zastavnik, H. Sol, J. Degrieck, W. Van Paepegem*	Finite element model updating using thermographic measurements: comparison between materials with high and low thermal conductivity, *J. Peeters, G. Arroud, B. Ribbens, J. Dirckx, G. Steenackers*
17:00	Non-destructive evaluation of historic natural stone masonry regarding thickness and voids, *F. Lehmann, M. Krüger*	Highly nonlinear solitary waves for the NDT of slender beams, *P.Rizzo, A. Bagheri, E. La Malfa Ribolla*	Evaluation of self-healing TDCB polymer testing configuration by means of optical and acoustic techniques, *E. Tsangouri, X.K.D. Hillewaere, D. Garoz, F. Du Prez, W. Van Paepegem, D.G. Aggelis, D. Van Hemelrijck*
17:20	Evaluation of seismic risk in regional areas by AE monitoring of historical buildings, *G. Lacidogna, P. Cutugno, F. Accornero, S. Invernizzi, A. Carpinteri*	Application of the SAFT at low frequencies for detection of the concentrated defect in sprinkler pipe, *L. Mažeika, V.Samaitis, R.Kažys, A.Wilkinson, M.Deere*	Detection of the interface between two metals by DC current stimulated thermography, *N.J. Siakavellas, J. Sarris*
17:40	Non destructive testing to perform service of the evaluation of conservation works, *R. Manganelli del Fa', A. Sansonetti, C. Riminesi, S. Rescic, M. Realini R.*	Nonlinear Ultrasonic Inspection of Friction Stir Welds, *M. Tabatabaeipour, J. Hettler, S. Delrue, K. Van Den Abeele*	Activation of self-healing mechanisms exploring several potential materials, *Minnebo P., D. Van Hemelrijck, D. G. Aggelis*
18:00	Non-contact contemporary techniques for the geometric recording of Cultural Heritage, *A. Georgopoulos*		Belgian Association for NDT: an overview of activities, *Aldo Gressani President of BANT (Belgian Association for Non-destructive Testing)*
18:20	A New Visual-based Diagnostic Protocol for Cultural Heritage exploiting the MPEG-7 Standard, *Anastasios Doulamis, Anastasia Kioussi, Antonia Moropoulou*		

19:00	**Social Event in MEMC Laboratory**

Day 2
Thursday 28/5/2015

	Room Q.B	Room Q.D
8:30	**Plenary talk, Basics and Applications of NDE based on Elastodynamics toward Infra-Dock for Concrete Structures, *Masayasu Ohtsu (room Q.D)***	
	Acoustic Emission, damage and lifetime prediction of composites **Chairs: Prof.N. Godin**	**Infra-asset assessment with innovative NDT 1** **Chair: Prof. T. Shiotani**
9:30	Identification of a critical time with acoustic emission monitoring during static fatigue tests on ceramic matrix composite: toward lifetime prediction, *Nathalie Godin, Pascal Reynaud, Mohamed R'Mili, Gilbert Fantozzi* ***(keynote)***	Strategic Maintenance Philosophy for Infra-Asset with Innovative NDT, *T. Shiotani* ***(keynote)***
10:00	Acoustic emission of fiber reinforced concrete under doublepunching indirect tensile loading, *D. Choumanidis, E. Komninou, P. Oikonomou, E. Badogiannis, P. Nomikos, A. Sofianos*	Experimental verification of a Rayleigh-wave based technique for detecting the depth of deteriorated concrete, *K.C. Chang, T. Shiotani, and S.B. Tamrakar*
10:20	Fracture Mechanism of CFRP-Strengthened RC Beam Identified by AE-SiGMA, *N. Alver, H. M. Tanarslan, Ö. Y. Sülün, E. Ercan*	Evaluation of grouting condition for PC structures with wide band ultrasonic waves, *M. Hashinoki, M. Hara, T. Kinoshita, K.C. Chang*
10:40	Acoustic Emission Testing of High-Temperature Process Vessels during Cool Down, *A. Anastasopoulos, D. Kouroussis, K. Bollas, D. Papasalouros*	Two-dimensional AE-Tomography based on ray-trace technique for anisotropic materials, *Y. Kobayashi, T. Shiotani*
11:00	Coffee Break (Q, room Nelson Mandela)	
	Application of NDT/SHM techniques to cultural heritage 5 **Chair: Prof. A. Saisi, Prof. A. Moropoulou**	**Infra-asset assessment with innovative NDT 2** **Chair: Prof. T. Shiotani, Prof. H-K. Chai**
11:10	Integration of EFD and IRT for moisture mapping on historic masonry: study cases in Northern Italy, *R. Olmi,C. Riminesi, E. Rosina*	Characterization of inclined surface crack in steel reinforced-concrete by multichannel R-wave measurements, *Foo Wei Lee, Hwa Kian Chai, Kok Sing Lim*
11:30	Pre-diagnostic prompt investigation of a historic bell tower by visual inspection and microwave remote sensing, *A. Saisi, C. Gentile, L. Valsasnini*	Ultrasonic Method for Predicting Residual Tensile Stress of Wedge Type Ground Anchors, *S.B. Tamrakar, T. Shiotani, and K.C. Chang*
11:50	Increasing durability of exterior plasters for historical buildings: innovative and steady tests for the characterization of water and vapor exchange/diffusion, *A. Sansonetti, S. Erba, E. Rosina*	Digital Image Correlation (DIC) and Acoustic Emission (AE) to characterise the structural behaviour of hybrid composite-concrete beams, *S. Verbruggen, S. De Sutter, S. Iliopoulos, D. Aggelis, T. Tysmans*
12:10	Lunch	

	Application of NDT/SHM techniques to cultural heritage 6 **Chair: Prof. A. Saisi, Prof. A. Moropoulou**	**Infra-asset assessment with innovative NDT 3** **Chair: Prof. T. Shiotani, Prof. H-K. Chai**
13:10	Digital Cultural Heritage - A Challenge for the Chemical Engineering: Contextualizing Materials in a Holistic Framework, *M. Ioannides, M.L. Vincent, E. Alexakis, C. M. Coughenour, M.F. Gutierrez, V. M. Lopez-Menchero Bendicho, A. Moropoulou, D. Fritsch* **(Keynote)**	Evaluation of X-ray CT Image Properties of Cracked Concrete by Spatial Parameter Analysis, *Tetsuya Suzuki, Tomoki Siotani* ***(Keynote)***
13:40	Focus on soluble salts diffusion: the study cases of Leonardo monochrome at Sala delle Asse (Milan), *A. Sansonetti, M. Realini , S. Erba, E. Rosina*	Mechanical and acoustic behavior of fire damaged plain and fiber reinforced concrete, *A. C. Mpalaskas, D. A. Exarchos, D. G. Aggelis, T. E. Matikas*
14:00	Integrated ND Methodologies for the Evaluation of the Adhesion of Frescoes on Stone Masonry Walls, *M.R. Valluzzi, G. Salemi, R. Deiana, E. Faresin, G. Giacomello, M. Giaretton, M. Panizza, M. Pasetto, S. Calò, M. Battistella, A. Frestazzi*	An ultrasonic method utilizing anchors to inspect steel-plate bonded RC decks , *N. Ogura, H. Yatsumoto, K.C. Chang, T. Shiotani*
14:20	Application of the mortar penetration test to the cultural heritage of Basilicata, Italy, *D. Liberatore, N. Masini, L. Sorrentino, V. Racina, L. Frezza, M. Sileo*	
14:40	ND techniques in the monitoring and preservation of the Cultural Heritage: state of the art and future prospects, *E. Zendri, L.Falchi, G.Driussi*	
15:00	Coffee Break (Q, room Nelson Mandela)	

17:00	**Chocolate Planet (details will follow)**

19:00	**Conference Dinner in the centre of Brussels**

Day 3
Friday 29/5/2015

8:30	**Plenary talk: Resonant Defects: A New Approach to Highly-Sensitive Defect-Selective Imaging, *Igor Solodov (room Q.D)***

	Room Q.B	Room Q.D
	Biological Applications **Chair: Prof. P. Rizzo**	**Ultrasonic Structural Health Monitoring** **Chair: Prof. M. Gresil**
9:30	A noninvasive approach for the assessment of dental implants stability, *P.Rizzo, E. La Malfa Ribolla* ***(Keynote)***	Acousto-ultrasonic Structural Health Monitoring of Aerospace Composite Materials, *M. Gresil, A. Muller, C. Soutis* ***(Keynote)***
10:00	Monitoring techniques for nanocrystalline stabilized zirconia from some medical prosthesis, *Adriana Savin, Mihail Liviu Craus, Vitalji Turchenko, Alina Bruma*	Plastic pipe welds inspection using neural networks approach, *Gediminas Genutis, Liudas Mažeika, F. Hagglund, M. Troughton*
10:20	Kinetic sensor for 3D modelling of logs in small sawmills, *J. Antikainen, D. Xiaolei*	The comparison between TIME-OF-FLIGHT DIFRACTION (TOFD) and conventional UT capabilities in defect sizing and monitoring for steel structures under cyclic and dynamic loading, *A. Yousefi, M. Esmaeilian, D. Ghasemi*
10:40	Raman Spectroscopy: An Emerging Technique for Non-Destructive Clinical Testing, *M. G. Okoula, C. G. Kontoyannis*	Guided Wave Tomography based inspection of CFRP plates using a probabilistic reconstruction algorithm, *J. Hettler, M. Tabatabaeipour, S. Delrue and K. Van Den Abeele*
11:00	Coffee Break (Q, room Nelson Mandela)	
	Funding Opportunities in the field of NDT/SHM/Engineering **Chair: Prof. M. Forde**	**Embedded Sensors** **Chair: Prof. A. Deraemaeker**
11:20	Horizon 2020: getting started, *Anneke Geyzen, European Liaison Office*	Investigations on the structural integrity and functional capability of embedded piezoelectric modules, S. Geller, *A. Winkler, M. Gude*
11:40	Funding your research and innovation project: how can we help you? *Ms. Tania Van Loon, National Contact Point Brussels Manager at impulse.brussels*	Healing performance monitoring using embedded piezoelectric transducers in concrete structures, *G. Karaiskos, E. Tsangouri, D.G. Aggelis, A. Deraemaeker and D. Van Hemelrijck*
12:00	European Research Efforts in SHM, *Michael Kyriakopoulos, European Comission*	Fibre-reinforced composites with embedded piezoelectric sensoractuator-arrays, *A. Winkler, M. Dannemann, E. Starke, N. Modler*
12:20	Lunch	
	Electromagnetics and X-rays	**Applications 3**

	Chairs: Prof. J. De Grieck, Prof. C. Glorieux	**Chairs: Prof. A. Savin, Prof. T. Kek**
13:20	Micro-CT as a well-established technique to investigate the internal damage state of a composite laminate subjected to fatigue, *G. Chiesura, G. Luyckx, E. Voet, W. Van Paepegem, J. Degrieck, L. Van Hoorebeke, M. Boone, J. Dhaene* ***(Keynote)***	Detection of Damaged Tool in Injection Molding Process with Acoustic Emission, *Tomaž Kek, Dragan Kusić, Janez Grum* ***(Keynote)***
13:50	Damage detection and classification in composite structure after water-jet cutting using computed tomography and wavelet analysis, *A. Katunin*	Water-Absorption-Measurement instrument for building facades, *M. Stelzmann, U. Möller, R. Plagge*
14:10	Post Weld Heat Treatment surface residual stress measurements using X-ray diffraction, *S.Kumar, M.J.Tan, B.S.Wong, N.Weeks*	An Experimental Evaluation of Electromagnetic Acoustic Transducers at High Temperature Environment for the Inspection of Concentrated Solar Plants, *Maria Kogia, Abbas Mohimi, Liang Cheng, Vassilios Kappatos, Cem Selcuk, Tat-Hean Gan*
14:30	Enhancement of spatial resolution using metamaterial sensor in nondestructive evaluation, *Adriana Savin, Rozina Steigmann, Alina Bruma*	Advances in Remote Condition Monitoring of High Speed Railway Trackbed, *M. Lim, S. Ivanov, R. De Bold, A. Giannopoulos, M.C. Forde & D.P. Connolly*
14:50		Portable automated radio-frequency scanner for non-destructive testing of carbon-fibre-reinforced polymer composites, *B. Salski, P. Theodorakeas, I. Hatziioannidis, A. Y. B. Chong, S.M. Tan, V. Kappatos, C. Selcuk, T.H. Gan, M. Koui*
15:10	CLOSING ADDRESS (room Q.D)	
15:30	Coffee Break (Q, room Nelson Mandela)	
16:00	Rilem TC 239-MCM meeting in ARCH department, Kb	