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NON-HOMOGENEITY EFFECT IN THE SPHERICAL SHELL BY USING SETH'S THEORY

NEHOMOGENI EFEKAT U SFERNOJ LJUSCI PRIMENOM TEORIJE SETA

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Keywords
- elastic-plastic
- pressure
- spherical shell
- stresses
- non-homogeneity

Abstract

This paper presents nonlinear deformation behaviour of non-homogeneous spherical shell examined under pressure by using Seth's transition theory. It has been seen that for increased material compressibility in thickness direction, the circumferential stress in the spherical shell reaches maximum at the external surface, but is reverse in the case of a deceasing compressibility in the thickness direction. The spherical shell of non-homogeneous material (non-homogeneity increases radially) is on the safer side of design. Hence, the more use of non-homogeneous material (non-homogeneity increases radially) may be beneficial for manufacturing spherical shells as they provide longer service life than shells of homogeneous material under identical conditions.

Ključne reči
- elastičnost-plastičnost
- pritisak
- sferna ljuska
- naponi
- nehomogenost

Izvod

U radu je prikazano nelinearno ponašanje deformacije nehomogene sferne ljuske ispitane pod pritiskom primenom prelazne teorije Seta. Pokazano je da sa povećanjem stišljivosti materijala u pravcu debljine, obimni naponi sferne ljuske dostižu maksimum na spoljnoj površini, ali se dešava i obrnuto u slučaju pada stišljivosti materijala u pravcu debljine. Sferna ljuska od nehomogenog materijala (nehomogenost raste radijalno) jeste na sigurnijoj strani projektovanja. Stoga, veća upotreba nehomogenog materijala (nehomogenost raste radijalno) može biti korisna u proizvodnji sfernih ljuski, jer pružaju duži vek trajanja od sfernih ljuski napravljenih od homogenog materijala pod istim uslovima.

INTRODUCTION

Non-homogeneous materials are the specific class of composite materials in which the constituents are graded in one or more direction with continuous variation to achieve the desired properties. The smooth grading of constituents results in better thermal properties, higher fracture toughness, improved residual stress distribution and the reduced stress intensity factors. These properties allow non-homogeneous structures to withstand high pressure under elevated thermal environment. Therefore, the analysis of non-homogeneity in the spherical shell through a mathematical model by taking one and all complexities into consideration are the major concern of researchers /1/. In real situations the non-homogeneity of mechanical properties may be caused by numerous phenomena and its nature may be very diverse. First, it is evident that a universal property of bodies occurring in practice is their microscopic non-homogeneity. It is well known that there have been many successful attempts to include microscopic non-homogeneity in the structure of continuum theory /2/. Some degree of non-homogeneity is present in the wide class of materials such as hot-rolled copper, aluminium and magnesium alloys. Vu et al. /3/ have discussed the problem on the nonlinear stability analysis of thin annular spherical shells made of functionally graded materials (FGM) on elastic foundations under external pressure and temperature. Classical thin shell theory in terms of shell deflection and stress function is used to determine the buckling loads and nonlinear response of FGM annular spherical shells. The Galerkin method is applied to obtain a closed form of load-deflection paths. An analysis is carried out to show the effects of material, geometrical properties, elastic foundations and combination of external pressure and temperature on the nonlinear stability of annular spherical shells. Yiqi et al. /4/ solved the problem of interfacial damage analysis of shallow spherical shell with non-homogeneous coating under low velocity impact. An interfacial damage analytical model is established on continuum theory-based interfacial damage constitutive relations. The A.E. Giannakopoulos's 2-D functionally graded material (FGM) contact model is applied to predict contact force. Motion equations for shallow spherical shell substrate and FGM coating are obtained by Reissner variation, respectively, and the dynamic analytical model is established by using interfacial connection relations to relate the motion equations for FGM coating and those for elastic shallow spherical substrate. The orthogonal collocation point method, the Newmark method and iterative method are used synthetically to solve the whole problem. Qiao et al. /5/ investigate the propagation characteristics of elastic guided waves in spherical shells with exponentially graded material in the radial direction. A new separation of variables technique to displacements is proposed to convert the governing equations of the wave motion to the second-order ordinary differential equations with variable coefficients. Further, by a variables transform technique, these equations are transformed to the Whittaker equations so that analytic solutions can be obtained. Atkočiūnas et al. /6/ have discussed the one of possible optimization methodologies for ideal elastic–plastic structures at shakedown and its application for shallow spherical shells having a prescribed geometry and affected by a variable repeated load, a system of external forces that may vary independently of each other. The problem deals with only time-independent upper and lower bounds of variations in external forces. The discussed concept of the structure at shakedown refers to the Melan theorem related to statically allowable admissible internal forces. Thus, for the discretization of the spherical shell, with the help of an assumption about small displacements, the equilibrium finite element method based on internal force approximation is applied. The article presents a discrete mathematical model for determining the optimal allocation problem with strength and stiffness requirements. All these authors mentioned above have analysed the problems considering the assumptions: (i) incompressibility condition; (ii) creep - strain laws like Norton; (iii) yield condition, like that of Tresca; (iv) associated flow rule. The necessity of using these ad-hoc semi-empirical laws in classical theory of elastic-plastic transition is based on an approach that the transition is a linear phenomenon which is not possible, /7/. Under elastic-plastic and creep transition, the fundamental structure of an object undergoes a change and rearranges themselves to cause non-linear effects. Therefore, it suggests that at transition behaviour, non-linear terms are significant and cannot be ignored. Generalized strain measures are useful in solving various problems of elastic-plastic by solving the nonlinear differential equations at transition points. This concept of generalized strain measures and transition theory has been applied to find transitional stresses in various problems (Gupta et al., /8-11/; Thakur et al., /12-28/). Thakur /13, 14/ discusses the problems in creep transition stresses of a thick isotropic spherical shell by infinitesimal deformation under steady state of temperature by using Seth transition theory. All these problems based on the recognition of the transition state as separate state necessitates showing the existence of the constitutive equation for that state. In this paper, we shall derive the results for spherical shell under pressure with the effect of non-homogeneity, on the basis of the concept of generalized strain measures and Seth's transition theory of elastic-plastic and creep. Seth, /28/, has defined the concept of generalized strain measures as:

$$e_{ii} = \int_0^{\overset{A}{e}_{ii}} \left[1 - 2\overset{A}{e}_{ii}\right]^{\frac{n}{2}-1} d\overset{A}{e}_{ii} = \frac{1}{n}\left[1 - \left(1 - 2\overset{A}{e}_{ii}\right)^{\frac{n}{2}}\right], \ i = 1,2,3 \qquad (1)$$

where: n is the measure; and $\overset{A}{e}_{ii}$ are the Almansi finite strain components. For n = –2, –1, 0, 1, 2, it gives Cauchy, Green, Hencky, Swainger, and Almansi measures, respectively. Non-homogeneity in the spherical shell has been taken as the compressibility of the material as:

$$C = C_0 r^{-k} \qquad (2)$$

where: $a \le r \le b$, C_0 and k are the constants. The results obtained have been discussed numerically and depicted graphically.

FORMULATION OF THE PROBLEM AND IDENTIFICATION OF THE TRANSITION POINTS

We consider a thick-walled spherical shell, whose internal and external radii are a and b, respectively subjected to uniform internal pressure, p, applied at the internal surface of the shell. It is convenient to use spherical coordinates (r,θ,ϕ), where θ is the angle made by the radius vector with a fixed axis, and ϕ is the angle measured round this axis. By virtue of the spherical symmetry, $\sigma_\theta = \sigma_\phi$ everywhere in the shell, due to spherical symmetry of the structure, the components of displacement in spherical co-ordinates (r,θ,ϕ) are given by:

$$u = r(1 - \beta), \ v = 0, \ w = 0$$

where: u, v and w are displacement components, u along the radial direction, β is position function, depending on r only. The generalized components of strain are given by Seth /7, 28/:

$$e_{rr} = \frac{1}{n}\left[1 - (r\beta' + \beta)^n\right], \ e_{\theta\theta} = \frac{1}{n}\left[1 - \beta^n\right] = e_{\phi\phi},$$
$$e_{r\theta} = e_{\theta\varphi} = e_{r\varphi} = 0 \qquad (4)$$

where: n is measure, and $\beta' = d\beta/dr$.

Stress-strain relation: the constitutive equation for stress-strain relations for isotropic material are given as /29/:

$$T_{ij} = \lambda\delta_{ij} I_1 + 2\mu e_{ij}, \quad (i,j = 1, 2, 3) \qquad (5)$$

where: T_{ij} are the stress components; λ and μ are Lame's constants; $I_1 = e_{11}$ is the first strain invariant. Substituting Eq.(4) in Eq.(5), the stresses are obtained as:

$$T_{rr} = \frac{\lambda}{n}\left[3 - 2\beta^n - (r\beta' + \beta)^n\right] + \frac{2\mu}{n}\left[1 - (r\beta' + \beta)^n\right],$$
$$T_{\theta\theta} = \frac{\lambda}{n}\left[3 - 2\beta^n - (r\beta' + \beta^n)\right] + \frac{2\mu}{n}\left[1 - \beta^n\right] = T_{\phi\phi}, \qquad (6)$$
$$T_{r\theta} = T_{\theta\phi} = T_{\phi r} = 0$$

Equation of equilibrium: the radial equilibrium of an element of the spherical shell requires:

$$\frac{dT_{rr}}{dr} = \frac{2}{r}(T_{\theta\theta} - T_{rr}) \qquad (7)$$

where: T_{rr} and $T_{\theta\theta}$ are the radial and circumferential stresses. For sufficiently small values of pressure, the deformation of the shell is purely elastic.

Boundary conditions: the boundary conditions are:

$T_{rr} = -p$ at $r = a$ and $T_{rr} = 0$ at $r = b$. (8)

Critical points or turning points: the points at which object changes its state from elastic to plastic and plastic to creep - are known as critical points or *transition points*. We can find these transition points from a nonlinear differential equation in β obtained by using Eqs.(6) in Eq.(7) as:

$$nP(P+1)^{n-1}\beta^{n+1}\frac{dP}{d\beta}=r\left(\frac{\mu'}{\mu}-\frac{C'}{C}\right)\Big[(3-2C)-\beta^n\times \times\left\{2(1-C)+(1+P)^n\right\}\Big]-2C'r(1-\beta^n)-n\beta^n P\times \times\left\{2(1-C)+(1+P)^n\right\}+2C\beta^n\left[1-(1+P)^n\right] \tag{9}$$

where: compressibility factor $C = 2\mu/\lambda + 2\mu$, $C' = dC/dr$, $\mu' = d\mu/dr$ and substitution $r\beta' = \beta P$ (P is function of β and β is function of r); β may be determined from this non-differential Eq.(9). The transition value of β from Eq.(9) are $P \to -1$ and $P \to \pm\infty$. Suppose r' and r are the unstrained and strained radii vectors of a point before and after deformation respectively, then $r' = r\beta$, and $\partial r'/\partial r = r\beta' + \beta = \beta(1 + P)$. These show that when $P \to -1$ then $\partial r'/\partial r \to 0$, $dr'/dr \to 0$, and so $P = -1$ corresponds to infinite extension. Similarly, $P \to \pm\infty$ corresponds to infinite contraction. The strain ellipsoid (see Borah, /30/) reveals that both above mentioned points are transition points. Hereby, we are only interested in finding elastic-plastic stresses corresponding to $P \to \pm\infty$ which are generated under the effect of pressure.

SOLUTION THROUGH PRINCIPAL STRESS

In order to find the plastic stresses, the transition function is taken through principal stress (see Seth /7, 28/; Gupta et al. /8-11/; Thakur et al. /12-28/). It has been shown that the asymptotic solution through the principal stress leads from elastic to plastic state at transition point $P \to \pm\infty$. We define the transition function as:

$$T_f = T_{rr} - \frac{3\lambda}{n} = \frac{2\mu}{nc}\left[C-\beta^n\left\{2(1-C)+(P+1)^n\right\}\right] \tag{10}$$

Taking the logarithmic differentiation of Eq.(10) with respect to r, we get:

$$\frac{d}{dr}(\log T_f)=\frac{\left[\begin{array}{l} r\left(\frac{\mu'}{\mu}-\frac{C'}{C}\right)\left[C-\beta^n\left\{2(1-C)+(1+P)^n\right\}\right]-rC'- \\ -n\beta^n P\left[2(1-C)+(1+P)^n\right]+2C'r\beta^n- \\ -nP(1+P)^{n-1}\beta^{n+1}\frac{dP}{d\beta}\end{array}\right]}{r\left[C-\beta^n\left\{2(1-C)+(1+P)^n\right\}\right]} \tag{11}$$

Substituting the value of $dP/d\beta$ from Eq.(9) and taking asymptotic value $P \to \pm\infty$, we get:

$$\frac{d}{dr}(\ln T_f) = -\frac{2C}{r} \tag{12}$$

On integrating Eq.(12), we get:

$$T_f = A\exp f(r) \tag{13}$$

where: A is a constant of integration which can be determined by the boundary condition and

$$f(r) = -\int\frac{2C}{r}dr. \tag{14}$$

By using Eqs.(10) and Eq.(13), we have the transition value T_{rr} as:

$$T_{rr} = A\exp f(r)+\frac{\lambda}{n}k_1 \tag{15}$$

where: $\lambda k_1/n$ is a constant of integration which can be determined by the boundary condition; $k_1 = [3 - (1 - d)^n]$ and d is a constant.

By using the boundary condition Eq.(8) in Eq.(15), we get:

$$A=\frac{-p}{\exp f(a)-\exp f(b)} \text{ and } \frac{\lambda}{n}k_1=-A\exp f(b) \tag{16}$$

Using Eq.(16) in Eq.(15), we get:

$$T_{rr} = A\left[\exp f(r)-\exp f(b)\right] \tag{17}$$

Substituting Eq.(17) into Eq.(7), we get

$$T_{\phi\phi} = T_{\theta\theta} = A\left[(1-C)\exp f(r)-\exp f(b)\right] \tag{18}$$

Equations (17) and (18) give the elastic-plastic transitional stresses for non-homogeneous compressible spherical shell under internal pressure. We introduce the non-homogeneity in spherical shell due to variable compressibility by Eq.(2), therefore Eqs.(17) and (18) become:

$$T_{rr}=\frac{-p\left[\exp(2C_0r^{-k}/k)-\exp(2C_0b^{-k}/k)\right]}{\exp(2C_0a^{-k}/k)-\exp(2C_0b^{-k}/k)}, \tag{19}$$

$$T_{\theta\theta}=T_{rr}+\frac{p\left[C_0r^{-k}\exp(2C_0r^{-k}/k)\right]}{\exp(2C_0a^{-k}/k)-\exp(2C_0b^{-k}/k)}, \tag{20}$$

and $$T_{\theta\theta}-T_{rr}=\frac{-p\left[C_0r^{-k}\exp(2C_0r^{-k}/k)\right]}{\exp(2C_0a^{-k}/k)-\exp(2C_0b^{-k}/k)}. \tag{21}$$

Initial yielding: it is seen from Eq.(21) that $|T_{\theta\theta} - T_{rr}|$ is maximal at internal surface (that is at $r = a$), therefore, yielding will take place at internal surface of spherical shell and Eq.(21) gives:

$$\left|T_{\theta\theta}-T_{rr}\right|_{r=a}=\left|\frac{-p\left[C_0a^{-k}\exp(2C_0a^{-k}/k)\right]}{\exp(2C_0a^{-k}/k)-\exp(2C_0b^{-k}/k)}\right|\equiv Y \tag{22}$$

where Y is yielding stress. The pressure required for initial yielding is given by:

$$p_i=\frac{p}{Y}=\left|\frac{\left\{\exp\left[\frac{2C_0}{k}(a^{-k}-b^{-k})\right]-1\right\}}{C_0a^{-k}\exp\left[\frac{2C_0}{k}(a^{-k}-b^{-k})\right]}\right|,\quad \forall k\neq 0 \tag{23}$$

Fully-plastic state: for fully plastic state approach C_0 tends to zero, we have the pressure required to attain full plasticity:

$$\left|T_{\theta\theta}-T_{rr}\right|_{r=b}=\lim_{C_0\to 0}\left|\frac{-p\left[C_0b^{-k}\exp(2C_0b^{-k}/k)\right]}{\left[\exp(2C_0a^{-k}/k)-\exp(2C_0b^{-k}/k)\right]}\right|\equiv Y \tag{24}$$

where Y is yielding stress. Pressure required for fully plastic state is given by:

$$p_f = \frac{p}{Y} = \left| \frac{2}{k} \left(\frac{a^{-k}}{b^{-k}} - 1 \right) \right|, \quad \forall k \neq 0 \tag{25}$$

Stresses from Eqs.(19) and (20) for fully plastic state become:

$$\sigma_r = -p_f \frac{R^{-k} - 1}{R_0^{-k} - 1}, \quad \sigma_\theta = -p_f \frac{\left(1 - \frac{k}{2}\right) R^{-k} - 1}{R_0^{-k} - 1}, \quad \forall k \neq 0 \tag{26}$$

where: $\sigma_r = T_{rr}/Y$, $\sigma_\theta = T_{\theta\theta}/Y$, $a/b = R_0$, and $r/b = R$ be the non-dimensional components of stresses and radii ratios. Equations (26) are same as obtained by Blazynski /31/ and Chakravorty /32/.

NUMERICAL RESULTS AND DISCUSSION

For calculating stresses based on the above analysis, the following values have been taken, $k = -1, -0.5, 0, 0.5, 1$ and $C_0 = 0.5$ respectively. From Figs. 1 and 2, the curves are produced between pressure required for initial as well as for fully plastic state along the radii ratio b/a. It is observed that for an increase in material compressibility in the thickness (or radial) direction (i.e. $k < 0$) of the spherical shell, higher pressure is required to yield the internal surface as compared to a material of decreasing compressibility in this direction (i.e. $k > 0$), but the reverse results are reported for fully plastic state. It can be seen from Table 1, that non-homogeneity in the spherical shell increases the percentage change of pressure to make the shell a fully plastic state.

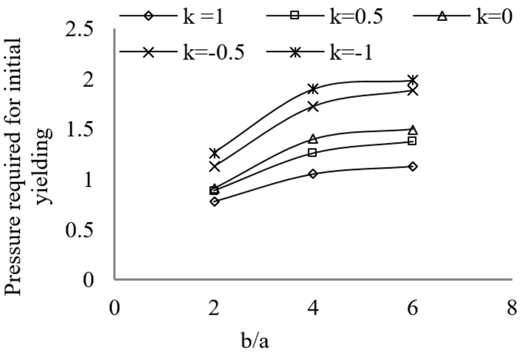


Figure 1. Pressure required for initial yielding at the internal surface for non-homogeneous spherical shell.

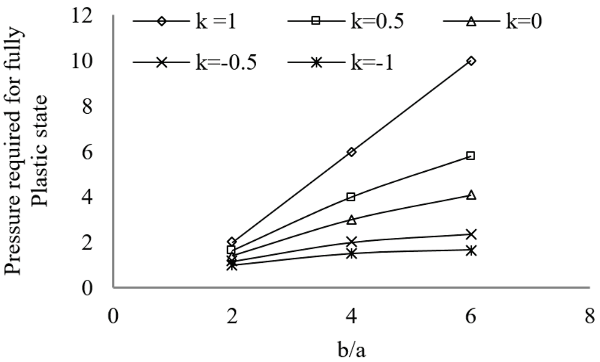
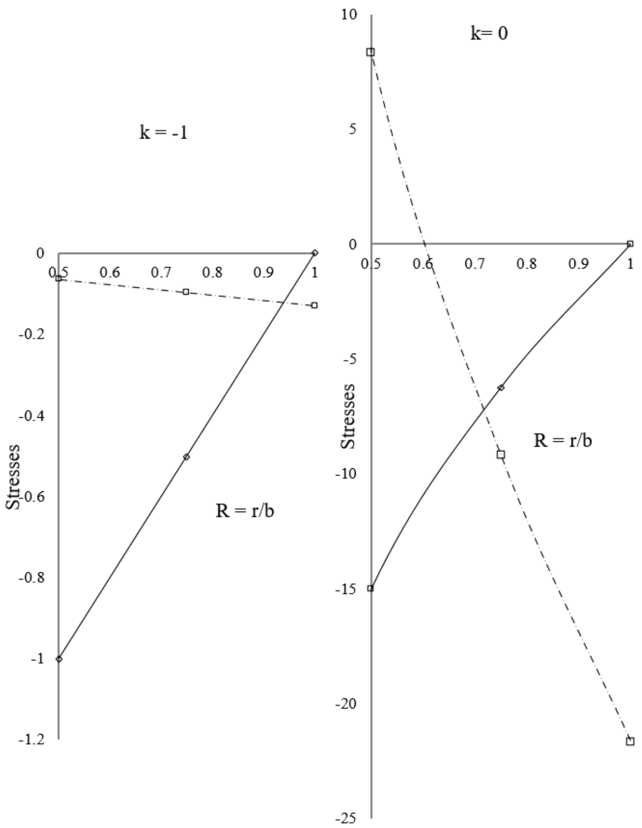


Figure 2. Pressure required for fully plastic state for non-homogeneous spherical shell.

Table 1. Pressure required for onset of initial yielding and fully plastic state in spherical shell with effect of non-homogeneity.

Radii ratio b/a	Non-homogeneity of spherical shell k	Pressure required for initial yielding p_i	Pressure required for fully plastic state p_f	% percentage $\left[\frac{\sqrt{p_f}-\sqrt{p_i}}{\sqrt{p_i}}\right].100$
2	-1	1.2464	1.001	0.049 %
4		1.9	1.5	22.47%
6		1.986	1.66	28.84%
2	-0.5	1.126	1.1715	8.235 %
4		1.729	2	41.42%
6		1.889	2.36	53.62%
2	0	0.91	1.3245	15.08 %
4		1.3	3	73.20%
6		1.2	4.07	101.74%
2	0.5	0.885	1.6568	28.71%
4		1.264	4	100%
6		1.38	5.79	140.62%
2	1	0.78	2.0000	41.42%
4		1.055	6	144.94%
6		1.1305	10	216.22%

In Fig. 3, curves are drawn between the stresses along the radii ratios $R = r/b$. It has been seen that when the material has increased compressibility in thickness direction, the circumferential stress in the spherical shell is maximal at the external surface, but reverse in case of a decreasing compressibility in the thickness direction. For a homogeneous material, circumferential stresses are maximum at the internal surface. The spherical shell of non-homogeneous material (non-homogeneity increases radially) is on the safer side of design. Hence, a wider use of non-homogeneous material (non-homogeneity increases radially) may therefore be beneficial for the manufacture of spherical shell as it provides a longer service life than for shells of homogeneous materials under identical conditions.



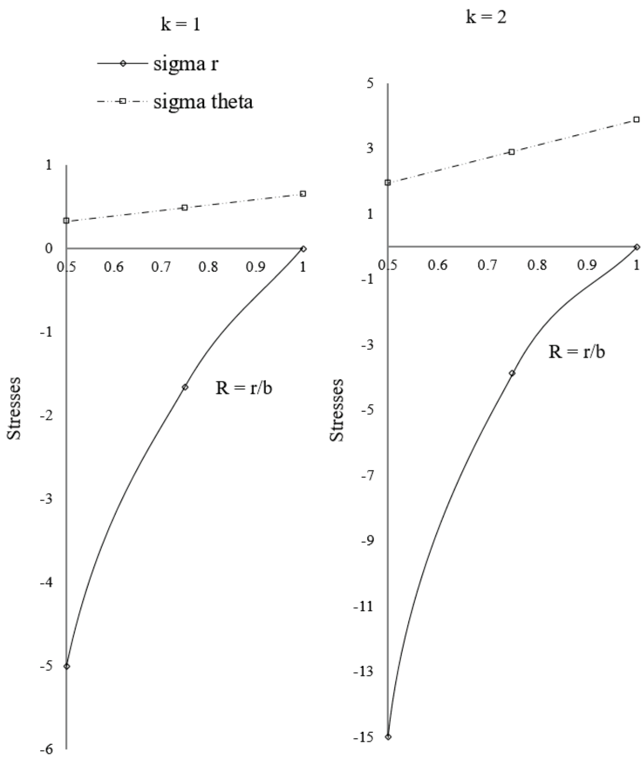


Figure 3. Stress distribution in a non-homogeneous spherical shell under internal pressure.

CONCLUSION

The spherical shell made of non-homogeneous material (non-homogeneity increases radially) is on the safer side of design. Hence, the more use of non-homogeneous material (non-homogeneity increases radially) may therefore be beneficial for the manufacture of spherical shell as they provide a longer service life than the for shells of homogeneous material under identical conditions.

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ESIS ACTIVITIES and
CALENDAR OF CONFERENCES, TC MEETINGS, and WORKSHOPS

January 14-16, 2018	ESIS TC-8 Meeting on Numerical Methods	Paris, France	flyer2018-1.pdf
March 14-16, 2018	XXXV Encuentro del Grupo Espanol de Fractura	Malaga, Spain	http://www.gef2018.es
April 12-13, 2018	ESIS TC-1 Meeting Workshop on 'Damage and Damage Tolerance of Welded Structures'	Prague, Czech Republic	Invitation ESIS TC 1 Spring 2018-1.pdf
May 10-11, 2018	ESIS TC-9 Meeting Innov. in Cement and Concrete Techn. Materials, Methods and Applications	Torino, Italy	info TC09-1.pdf
June 4-6, 2018	IGF Workshop Fracture and Structural Integrity: ten years of 'Frattura ed integrità Strutturale'	Cassino, Italy	link
June 17-20, 2018	1st International Conference on Theoretical, Applied and Experimental Mechanics (ICTAEM 1)	Paphos, Cyprus	https://www.ictaem.org/
July 1-5, 2018	18th International Conference on Experimental Mechanics (ICEM 2018)	Brussels, Belgium	http://www.icem18.org/
July 2-6, 2018	10th European Solid Mechanics Conference (ESMC 2018)	Bologna, Italy	http://www.esmc2018.org
July 5-6, 2018	2nd International Conference on Materials Design and Applications	Porto, Portugal	https://web.fe.up.pt/~mda2018/
July 8-11, 2018	8th Internat. Conference on Engineering Failure Analysis (ICEFA VIII)	Budapest, Hungary	link
August 25-26, 2018	ESIS Summer School in the scope of ECF22	Belgrade, Serbia	link
August 26-31, 2018	22nd European Conference of Fracture (ECF22)	Belgrade, Serbia	http://www.ecf22.rs
September 19-21, 2018	CP 2018- 6th International Conference on 'Crack Paths'	Verona, Italy	http://www.cp2018.unipr.it/
June 24-26, 2019	12th International Conference on Multiaxial Fatigue and Fracture (ICMFF12)	Bordeaux, France	link
March 30 - April 3, 2020	VAL4, 4th International Conference on Material and Component Performance under Variable Amplitude Loading	Darmstad, Germany	First Announcement