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ASSESSMENT OF THE BEHAVIOUR OF FATIGUE LOADED HSLA STEEL WELDED JOINT BY APPLYING FRACTURE MECHANICS PARAMETERS

PROCENA PONAŠANJA ZAVARENOG SPOJA HSLA ČELIKA OPTEREĆENOG NA ZAMOR PRIMENOM PARAMETARA MEHANIKE LOMA

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Keywords
- low-cycle-fatigue (LCF)
- J integral
- HSLA steel
- process equipment

Ključne reči
- niskociklični zamor (LCF)
- J integral
- niskolegirani čelik povišene čvrstoće (HSLA)
- procesna oprema

Abstract

From a fracture mechanics point of view on welded joints, it is assumed that the welded joint is pre-cracked such as that the fatigue life of the pre-cracked structure is then determined by the period of crack growth under variable load. Experimental data obtained by testing provide a substantial basis for a better understanding and an explanation of the phenomenon of material fatigue. Low cycle fatigue (LCF) occurs during the process of charging and discharging of reactors, pressure vessels and pipelines; the fatigue can be accelerated by an additional negative effect of temperature variation and the aggressive effect of the media contained inside the vessel, and during the exploitation of the equipment in the processing industry.

In the present paper the results are presented of J-integral measurements at LCF of a low-alloyed high strength steel (HSLA) weld metal used in the submerged arc welding process in the manufacture of pressure vessels.

Izvod

U zavarenim spojevima, sa gledišta mehanike loma, se pretpostavlja prisustvo prslina, gde se onda vek s obzirom na zamor takvih konstrukcija sa prslinama procenjuje vremenom rasta prsline pod promenljivim opterećenjem. Eksperimentalni podaci dobijeni ispitivanjem pružaju značajnu osnovu za bolje razumevanje i objašnjenje fenomena zamora materijala. Niskociklični zamor (LCF) se javlja u procesu punjenja i pražnjenja reaktora, posuda pod pritiskom i cevovoda; proces zamora može ubrzati dodatni negativan efekat promene temperature i efekat agresivne sredine sadržane u posudi, kao i tokom perioda eksploatacije opreme u procesnoj industriji.

U ovom radu prikazani su rezultati merenja J integrala pri niskocikličnom zamoru (LCF) metala šava niskolegiranog čelika povišene čvrstoće (HSLA), koji se koristi u proizvodnji posuda pod pritiskom postupkom zavarivanja pod praškom.

INTRODUCTION

Material fatigue can be clarified to a large extent by using the results obtained in experimental examination, particularly so when one should understand the behaviour of a crack in a material with a heterogeneous structure, such as the welded joint. Thus, we should conduct fracture mechanics fatigue testing of notched and pre-cracked specimens for determining the stress intensity factor, K_I and crack opening displacement, *COD*, or for determining the energy parameter, the J-integral. In addition, one should compare conditions for crack propagation at high-cycle fatigue (HCF) and low-cycle fatigue (LCF) on one hand, and the behaviour of the welded joint on the other hand. Based on it, one can get a picture of the welded joint behaviour affected by fatigue loading, and the possibility of J-integral application, as a universal parameter of elastic and plastic behaviour of a material with a crack, and their effect on the problem of fatigue-crack propagation.

In the present paper, the J-integral measurements at LCF for specimens of low-alloy high strength (HSLA) steel parent metal (PM) and the weld metal (WM) of their welded joints are presented.

MATERIAL

In these tests, the chosen material is NIONIKRAL 70B HSLA steel with welded joints performed by submerged arc-welding (SAW) with a US-80B wire.

The chemical composition of the tested material is presented in Table 1, and the chemical composition of the filler wire material for the SAW process in Table 2, in respect.

Table 1. Chemical composition of tested batch of NIONIKRAL 70B steel.
Tabela 1. Hemijski sastav ispitane šarže čelika NIONIKRAL 70B

Element	C	Si	Mn	Cr	Ni	Mo	P	S
wt. %	0.19	0.4	1.11	1.06	2.59	0.25	0.019	0.024

Table 2. Chemical composition of US-80B filler wire.
Tabela 1. Hemijski sastav US-80B žice za zavarivanje

Element	C	Si	Mn	Cr	Mo	P	S
wt. %	0.09	0.19	2.15	0.49	0.84	0.014	0.013

Tensile properties of the HSLA steel NIONIKRAL 70B are shown in Table 3, and the tensile properties of the weld metal (WM) created in the SAW process with the US-80B filler wire are shown in Table 4.

Table 3. Tensile properties of NIONIKRAL 70B steel.
Tabela 3. Zatezne karakteristike čelika NIONIKRAL 70B

Ultimate tensile strength (MPa)	Yield stress (MPa)	Elongation A_5 (%)	Reduction in cross section Z (%)
842	707	16	56.5

Table 4. Tensile properties of the tested welded joint WM.
Tabela 4. Zatezne karakteristike metala šava zavarenog spoja

Ultimate tensile strength (MPa)	Yield stress (MPa)	Elongation A_5 (%)	Reduction in cross section Z (%)
848	701	17	46.2

PLAN OF THE EXPERIMENT

Welded plates, specimens to be cut from the plates, order of cutting of the specimens and their testing are defined by the work plan.

Experimental testing the behaviour of NIONIKRAL 70B and weld metal has included the following:
1. Determination of PM and WM properties (results are shown in Tables 3 and 4);
2. Determination of fatigue-crack growth at HCF;
3. Measurement of specimen compliance and determination of dependence of compliance and crack length;
4. Establishment of dependence of fatigue-crack growth rate (increase of crack length per cycle) and range of stress-intensity factor;
5. Determination of J_R-curve and critical value of J_{Ic}-integral, and
6. Monitoring of J-integral value at LCF.

According to the plan for cutting specimens, shown in Fig. 1, from two welded plates dimensions of which were 550 × 330 × 12 mm round specimens for tensile tests and CT specimens for testing of fracture mechanics are made.

In this paper, the results of monitoring J-integral value at LCF are presented; other results can be found in /1/.

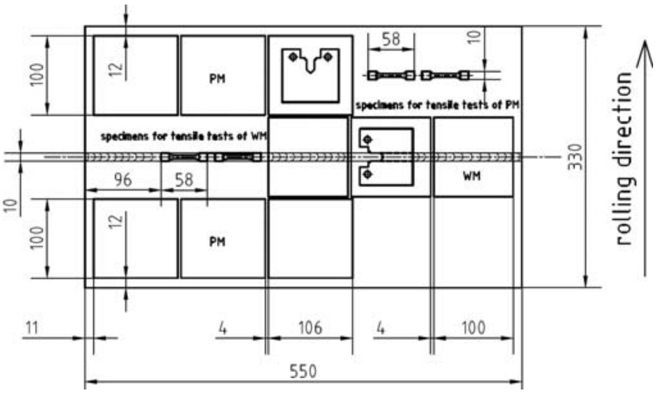

Figure 1. Scheme of cutting CT and tensile test specimens, cut from PM and WM of the SAW welded joint.
Slika 1. Šema rezanja CT i Zateznih epruveta za ispitivanje, isečenih iz PM i WM postupka zavarivanja SAW

TEST RESULTS OF J_R CURVES WITH LCF PHASES

The behaviour of HSLA steel in welded structures when affected by LCF is important, especially when a part of the structure contains a crack, /2-8/.

Testing Parent Metal Specimens

CT specimens (B = 11.85 mm; W = 86 mm; a_0 = 32 mm) from PM are tested for crack resistance, based on J_R-curves with phases of one-direction LCF for sake of analysing the effect of LCF on the shape of J_R curves and J_{Ic} value. Testing data on the subject specimen are shown in Table 5.

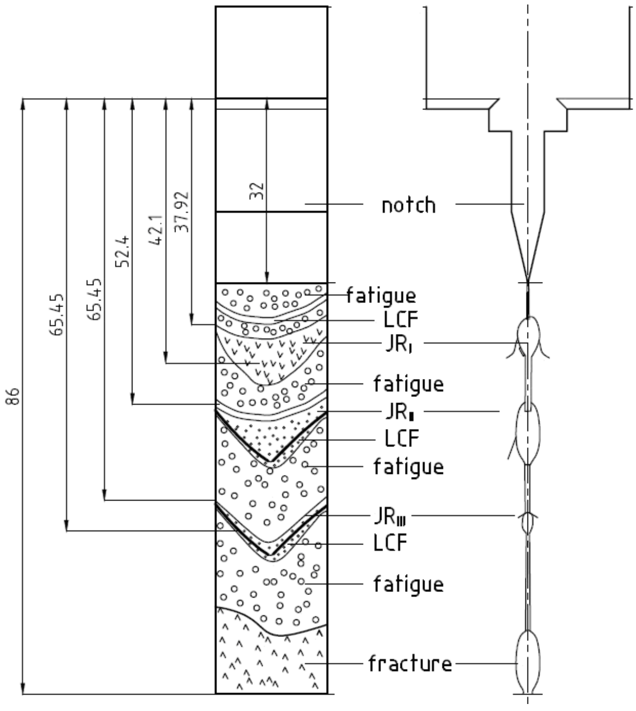

Figure 2. Fractured surface of CT specimen cut from PM.
Slika 2. Prelomna površina CT epruvete isečene iz PM

As one can see from Table 5, tests are conducted in a few phases as shown in Fig. 2. Taking into consideration the noticeable proportion of the LCF, in these tests the residual strain, measured by the magnitude of the residual COD, is monitored.

Table 5. Data from complex tests for determining J_R–curves with phases of LCF for CT specimens taken from PM.
Tabela 5. Podaci složenih ispitivanja za određivanje J_R–krivih sa fazama LCF za CT epruvete sa PM

	FATIGUE								COMPLIANCE				
										CRACK OPENING DISPLACEMENT (*COD*)			
Test phase	Upper force, F_{max}, kN	Lower force, F_{min},, kN	$R = F_{max}/F_{min}$	Frequency, *f*, Hz	Increase, No. of cycles, ΔN, cycle	Total No. of cycles *N*, cycle	Increase, crack length Δa, mm	Total crack length, *a*, mm	Max static force, kN	Residual, μm	Current, μm	Total, μm	Compliance *C*, μm/kN
A								32	50		408	408	8.16
								32	70		576	576	8.23
								32	30	67	244	311	8.13
								32	50	67	408	475	8.16
B	36.1	5.1	0.14	26	5000	5000	2.7	34.7	70	67	597	664	8.53
	50	5.7	0.11	1	300	5300	1.2	35.9	50	96	435	531	8.7
	36.1	5.1	0.14	28	10^4	15300	2.02	37.92	30	96	280	376	9.33
C							4.18	42.1	89	96	3808	3904	
D									40	2816	504	3320	12.6
	32	4.8	0.15	21	2000	2000	0.5	42.6	40	2816	512	3328	12.8
	32.2	5.6	0.17	21	5000	7000	1.8	44.4	40	2816	608	3424	15.2
	32.2	4.8	0.15	21	5000	12000	3.1	47.5	40	2864	741	3605	18.53
	32.2	4.8	0.15	21	5000	17000	3.8	51.3	40	2920	939	3859	23.46
	40	4	0.1	0.9	100	17100	1.1	52.4	40	2934	1019	3953	25.74
E								53.6	45.5	2994	2568	5562	
	43.5	3.5	0.08		30		0.22	53.82	43.5	4426	160	4586	
								54.65	41.75	4558	2400	6958	
	35	5	0.14		18		0.4	55.05	39	5806	128	5934	
F	24.9	5.3	0.21	20	4200	4200	9.35	64.4	10	5878	688	6566	68.8
G							0.7	65.1	18.75	5966	2760	8726	
	18.5	2	0.11		30		0.15	65.25	18	7454	152	7606	
							0.2	65.45	17.25	7482	2416	9898	74.3
H	11.25	1.25	0.11	20	5010	5010	4.05	69.5					
	8.7	0.85	0.11	20	2100	7110	7.3	76.8					

A–static tension for determination of compliance; B–fatigue-crack propagation a_{0I}; C–J_R-curve; D–fatigue-crack propagation a_{0II} with determination of compliance; E–J_{RII}-curve with LCF phases; F–HCF; G–J_{RIII}-curve with LCF phase; H–HCF.

Testing Weld Metal Specimens

The testing plan for the CT specimen (B = 11.8 mm; W = 86 mm; a_0 = 32 mm) with a notch in the WM differs from the previous one, as in this testing the LCF has had the most important role. The data from these tests are presented in Table 6, but it should be noted that monitoring of the test data was stopped after the second LCF (R ≈ 0.5).

Table 6. Data from complex tests for determining J_R-curves with phases of LCF for CT specimens taken from WM.
Tabela 6. Podaci složenih ispitivanja za određivanje J_R–krivih sa fazama LCF za CT epruvete sa WM

		FATIGUE								COMPLIANCE				
											CRACK OPENING DISPLACEMENT (*COD*)			
Test phase	Registered data point	Upper force F_{max}, kN	Lower force F_{min}, kN	$R = F_{min}/F_{max}$	Frequency, *f*, Hz	Increase No. of cycles, ΔN, cycle	Total No. of cycles, *N* cycle	Increase, crack length, Δa, mm	Total crack length , *a*, mm	Max. static force, kN	Residual, µm	Current, µm	Total, µm	Compliance *C*, µm/kN
A	1								32	35		242	242	6.93
B	2	36	3.6	0.1	25	200	200	0.5	32.5	35		252	252	7.2
	3	33	3.3	0.1	25	27600	27800	1.5	34	35		261	261	7.46
	4	33	3.3	0.1	25	14600	42400	2.4	36.4	35		280	280	8
C	5							4.1	40.5	88	944	915	1859	10.4
D	17	71	7.1	0.1	0.5	50	50			70		840		12
	18	70.5	7.05	0.1	0.5	50	100			69		862		12.5
	19	69	6.9	0.1	0.5	50	150			67		911		13.6
	20	66	6.6	0.1	0.5	50	200			62		992		16
	21	62	6.2	0.1	0.5	50	250			57		1049		18.4
	22	57	5.7	0.1	0.5	50	300			54		1064		19.7
	23	53	5.3	0.1	0.5	50	350			48		1113		23.2
	24	46	4.6	0.1	0.5	50	400			41		1148		28
	25	38	3.8	0.1	0.5	50	450			32		1145		35.8
	26	27	2.7	0.1	0.5	50	500	21	61.5	19	1500	906	2406	47.7
E	27	19.84	9.9	0.5	0.5	50	50			22		1084		49.3
	28	21.92	10.96	0.5	0.5	50	100			21.6		1080		50
	29	21.52	10.76	0.5	0.5	50	150			213		1075		50.5
	30	21.36	10.68	0.5	0.5	50	200			21.2		1087		51.3
	31	20.96	10.48	0.5	0.5	50	250			20.8		1096		52.7
	32	20.64	10.32	0.5	0.5	50	300			20.6		1092		53
	33	20.16	10.08	0.5	0.5	50	350			20		1094		54.7
	34	19.68	9.84	0.5	0.5	50	400	5.3	66.8	19.4	1800	1100	2900	56.7
F								8.2	75					

A–static tension; B–HCF with determination of compliance; C–J_R curve; D–LCF immediately after J_R curve determination; E–LCF R ≈ 0.5; F–final HCF.

DISCUSSION

Testing PM Specimens

The original compliance of the specimen with a notch in the PM is determined by static loading (test phase A in Table 5).

Residual strain at the point at which the data were registered, 3, resulted from exceeded yield stress limit and small extension of the root notch. In phase B, the fatigue crack 37.92 mm-long was initiated, with initial and final HCF between which 300 cycles of LCF, as designated in

Fig. 2, were realized. Fatigue was interrupted from time to time for measuring the compliance. After that, standard determination of J_{Ic} in phase C using J_{RI} curve followed. Crack propagation in phase C was 4.18 mm and the value obtained, $J_{Ic} = 212.78$ kJ/m^2, is in accordance with the results of previous tests. Upon completion of phase C, COD measurements resumed from zero (knife edges that support the gauge arms were moved, as the full working range of the COD measuring device of 4 mm was exceeded). It was then that testing of the specimen was interrupted for the first time. In the next phase, D, the specimen was again subjected to fatigue, with determination of compliance at intervals. After 4 HCF cycles, 100 cycles of LCF followed. The specimen prepared in that way, with initial fatigue-crack length of $a_{02} = 52.4$ mm, was subjected to complex testing, phase E, by applying monotonous loading and successive unloading.

Testing WM Specimens

Tests started with three successive HCF, during which an increase of physical crack length 4.4 mm was attained, so that static loading *F–COD* was conducted with initial fatigue crack of 36.4 mm. After a sufficient number of unloading points, the value of plane-strain fracture toughness is obtained, LCF was tested with minimum force – maximum force ratio R ≈ 0.1. When the value of amplitude of upper force dropped below 20 kN, the testing of LCF resumed at R ≈ 0.5. To mark the attained crack length, we resumed with HCF until specimen fracture. In Fig. 3, the appearance of fracture surface is given, showing the differences in the behaviour of WM induced by heterogeneous structure and the existence of defects. The face of fatigue crack is blocked in development on one side, probably because of the existence of some defect in the structure (surface A in Fig. 3). That is why the crack face under static loading has had the shape of an irregular triangle (surface B in Fig. 3), with clear flat fracture in the crack plane, that only after crack growth of 1.4 mm deflects at an angle of 45° in the direction of maximal tangential stresses (plane stress state). In the initial phase of LCF, surface C in Fig. 3, the crack first propagates along the edges of the specimen, the face line becomes more regular in shape and the fatigue crack propagates, but still under conditions of the plane stress state. The effect of the fusion line becomes apparent. Namely, at the side surfaces fracture develops at the boundary between the heat-affected zone (HAZ) and the WM. One should also observe the surface D, where fracture is partially brittle due to structural defects in WM. The HCF characteristic for the crack length shows a similar fracture surface, and it is only in the final stage of fracture that shear lips form again.

CONCLUSION

The experimental procedure for the analysis of material crack resistance using fracture mechanics parameters for three types of effective loading (HCF, monotonously increased loading and LCF), as well as at combined loading (monotonously increased loading with LCF phases), is presented. By applying the above specified loadings to the PM of HSLA steel NIONIKRAL 70B and its WM obtained by SAW welding procedure, the properties relating to the resistance of these two constituents of a welded joint are determined and compared. The values obtained, $J_{Ic} \approx 210$ kJ/m^2 for PM and $J_{Ic} \approx 90$ kJ/m^2 for WM, indicate a degradation of the joint properties in WM. More inferior properties of the joint in WM are also indicated by decrease of the J-integral value in the LCF phases.

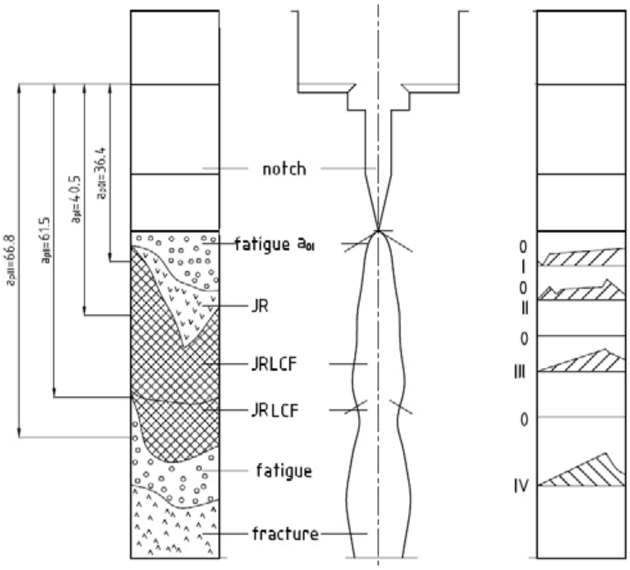

Figure 3. Fractured surface of CT specimen cut from WM.
Slika 3. Prelomna površina CT epruvete isečene iz WM

ACKNOWLEDGMENTS

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Selected list of Conferences and Meetings in 2013 — Izbor konferencija i skupova u 2013

FRaMCoS-8 — 8th International Conference on Fracture Mechanics of Concrete and Concrete Structures
Dates: 10 Mar 2013 → 14 Mar 2013 Location: Toledo, Spain
Abstract: The IA-FraMCoS (International Association of Fracture Mechanics for Concrete and Concrete Structures) was founded in 1992 in USA to promote and advance the theoretical and experimental aspects of fracture mechanics and cracking of concrete structures.
http://www.framcos8.org/frontal/Objectives.asp

GAMM 2013 — 84th Annual Meeting of the International Association of Applied Mathematics and Mechanics
Dates: 18 Mar 2013 → 22 Mar 2013 Location: Novi Sad, Serbia
Topics: Multi-body dynamics, Biomechanics, Damage and fracture mechanics, Structural mechanics, Nonlinear oscillations, Material modelling in solid mechanics, Coupled problems, Multiscales and homogenization, Laminar flows and transition, Turbulence and reactive flows, Interfacial flows, Waves and acoustics, Flow control, Applied analysis, Applied stochastics, Optimization, Applied and numerical linear algebra, Numerical methods of differential equations, Optimization of differential equations, Dynamics and control, Mathematical signal and image processing, Scientific computing, Applied operator theory, History of mechanics
http://www.dmi.uns.ac.rs/gamm2013 Contact: Prof. Dr Ljiljana Cvetković; Phone: +381214852791; Email: office_gamm13@dmi.uns.ac.rs

WOM 2013 — 19th International Conference on Wear of Materials
Dates: 14 Apr 2013 → 18 Apr 2013 Location: Portland, United States
Topics: Computational mechanics, Experimental mechanics, Fatigue, Fracture mechanics
http://www.wearofmaterialsconference.com/

ICMFF10 — The Tenth International Conference on Multiaxial Fatigue & Fracture
Dates: 03 Jun 2013 → 06 Jun 2013 Location: Kyoto, Japan
Topics: Fatigue, Fracture mechanics
http://www.ritsumei.ac.jp/~sakanem/ICMFF10-Home.html

ICAF 2013 — International Committee on Aeronautical Fatigue and Structural Integrity, Conference and Symposium
Dates: 03 Jun 2013 → 07 Jun 2013 Location: Jerusalem, Israel
Topics: Structural integrity, Advanced material structures, Fatigue testing, Life-extension and structural repairs, Structural health and loads monitoring, Non-destructive inspections (NDI), Crack and damage formation and growth, Corrosion and environmental control. Life prediction methods, Advanced finite-element modeling, Probabilistic modeling of structural integrity, Risk-analysis, Cyclic and environmental testing of components and materials
http://www.icaf2013.org/

ICOSSAR 2013 — 11th International Conference on Structural Safety & Reliability
Dates: 16 Jun 2013 → 20 Jun 2013 Location: Columbia University, New York, NY
Topics: Theoretical developments and practical applications related to the uncertainty, safety, risk and reliability of structures and systems in civil engineering, mechanical engineering, aerospace engineering, marine/offshore engineering, industrial engineering, nuclear engineering, materials science, environmental engineering, architecture, urban planning, geosciences and social sciences will be addressed. Multi-disciplinary approaches are particularly welcome.
http://icossar2013.org/conference-topics/

IRF 2013 — 4th International Conference on Integrity, Reliability & Failure
Dates: 23 Jun 2013 → 27 Jun 2013 Location: Funchal (Madeira), Portugal
Topics: Aircraft structures, Automotive structures, Biomechanics, Civil engineering, Composite materials & structures, Computational mechanics, Experimental mechanics, Fatigue, Fracture mechanics, Pressure vessels & piping, Railways, Reliability
http://paginas.fe.up.pt/clme/IRF2013/index.htm

SMiRT-22 — 22nd International Conference on Structural Mechanics in Reactor Technology
Dates: 18 Aug 2013 → 23 Aug 2013 Location: Marriott Marquis, San Francisco, California, USA
Topics: Mechanics of Materials, Fracture Mechanics and Structural Integrity, Applied Computation, Simulation and Animation, Characterization of Loads, Modeling, Testing and Response Analysis of Structures, Systems and Components, Design and Construction Issues, Safety, Reliability, Risk and Margins, Issues Related to Operations, Inspection and Maintenance, Fuel Cycle Facilities, Waste Management and Decommissioning, Challenges of New Reactors
http://www.smirt22.org/

LCF7 — The Seventh International Conference on Low Cycle Fatigue
Dates: 09 Sep 2013 → 13 Sep 2013 Location: Aachen, Germany
http://www.dvm-berlin.de/index.php?id=587&tx_seminars_pi1[showUid]=46

High-speed imaging for dynamic testing of materials and structures
Dates: 18 Nov 2013 → 20 Nov 2013 Location: London, United Kingdom
Abstract: An understanding of the dynamic behaviour of materials is essential for informing structural performance for e.g. crashworthiness, manufacturing capability, blast mitigation. Numerical simulation has seen spectacular progress with the advent of faster and cheaper computing power. However, such computations require detailed material models for which parameters have to be identified experimentally.
http://aptd.iopconfs.org

Fatigue Design 2013
Dates: 27 Nov 2013 → 28 Nov 2013 Location: Senlis, France
Topics: Fatigue, Fracture mechanics
http://www1.cetim.fr/fatiguedesign