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# THE ANALYSIS OF HYSTERESIS IN LOW CYCLE FATIGUE OF STEEL DAMPERS FOR EARTHQUAKE APPLICATION

## ANALIZA HISTEREZISA NISKOCIKLIČNOG ZAMORA ČELIČNIH DAMPERA ZA PRIMENU PRI ZEMLJOTRESU

*Abstract*

*Each civil engineering structure inevitably passes the phase of low cycle fatigue during strong impact loads of the earthquake, and light structures often fail due to loss of local or global stability (local buckling or deflection of structural components.*

*It is practically impossible to understand the behaviour of buildings subjected to seismic loads without base knowledge of behaviour of structural components during low-cycle fatigue process as well as the global stability of the structures during all phases of earthquake action.*

*Low cycle fatigue is examined theoretically and experimentally, using damage mechanics concept. Special attention is paid to ultra low cycle fatigue, in the sense Dufailly-Lemaitre. The theory is applied on dampers for strengthening structures damaged in the earthquake. Theoretical considerations are also experimentally checked.*

*Izvod*

*Svaka građevinska konstrukcija neminovno prolazi fazu niskocikličnog zamora pod dejstvom jakih udarnih opterćenja pri zemljotresu, a lake konstrukcije često stradaju zbog gubljenja lokalne ili globalne stabilnosti (lokalno izbočavanje ili izvijanje elemenata konstrukcije).*

*Praktično je nemoguće razumeti ponašanje zgrada izloženih zemljotresnom opterećenju bez osnovnog znanja o ponašanju konstrukcijskih komponenti tokom procesa nisko cikličnog zamora, kao ni stabilnost konstrukcije tokom svih faza dejstva zemljotresa.*

*Niskociklični zamor je istraživan teorijski i eksperimentalno, koristeći koncept mehanike oštećenja. Posebna pažnja je posvećena ultra niskocikličnom zamoru, u smislu Difaji-Lemetra. Teorija je primenjena na dampere za ojačavanje konstrukcija oštećenih zemljotresom. Teorijska razmatranja su takođe eksperimentalno proverena.*

## INTRODUCTION

Seismic loading, responsible for the rupture during earthquake, is characterized by two features. It is an impact (shock) loading, at the same time being variable. The effect of shock is hardly controllable, due to load intensity and extremely short time in which it is applied. Anyhow, the effect of variability can be used to reduce load intensity by applying a properly designed damper. For that the effect of variable loading has to be considered in more detail.

The effect of variable loading, well known as fatigue, is very early recognised, /1/. At the number of cycles above 105 of applied variable load producing maximal stress well bellow nominal yield stress, a fatigue crack can be initiated from an existing defect in a component and extend due to load stress range, in many cases up to final fatigue fracture. For this situation Wöhler proposed the relation between stress ratio in a cycle and number of cycles to failure, and this relation is still one of basic data for material behaviour during fatigue process. It is known as high cycle fatigue (HCF). In this case plastic strain occurs at microscopic level in a way that dissipative energy is small and negligible compared to the reversible elastic energy involved. For that, the fracture surface of the failed component is flat and smooth, normal to loading direction, with negligible plastic deformation and no tearing appearance, which is typical for fracture of ductile material above yield stress.

The effect of variable loading can be recognized also at low number of cycles as low cycle fatigue (LCF). It is generally accepted that LCF occurs in $10^2$ to $10^4$ cycles, when the applied load is close to yield stress level, or slightly above it. In that case, a significant part of energy is spent for plastic deformation, and the ratio between plastic energy, $\Delta W_p$, and elastic energy, $\Delta W_e$, is typically amounted to be $\Delta W_p/\Delta W_e = 1 \div 10$. Fracture surface is rough, with tearing appearance of ductile fracture.

Neither high cycle nor low cycle fatigue can be directly applied in the analysis when the number of cycles during seismic loading is very (ultra) low, typically 2 to 20. A new approach should be involved, as it has been proposed by Dufailly and Lemaitre, /2/, suggested to introduce a new term – ultra low cycle fatigue (ULCF). Anyhow, there is no sufficient knowledge to describe the behaviour of loaded components under so low number of cycles, and experience gathered from HCF and LCF experimental research and by fatigue failure of structures in service are available to consider material response to typical earthquake loading.

In ULCF the dissipative work and displacement beyond yielding are much larger than in elastic range, and consequently the energy for plastic strain is much larger than for elastic. This situation is important for dampers applied to strengthen structures damaged by earthquake. For that the history of plastic strain presented by the hysteresis diagram, indicating the relationship between stress and strain, should be analysed. Anyhow, the basic effects on fatigue behaviour of material in ULCF should be explained and understood in order to prevent catastrophic earthquake effects.

## LOW CYCLE FATIGUE OF STEEL

From the very beginning, problems of failures caused by fatigue damage, /1/, have been solved empirically, mainly using the experience gathered from case studies and applying "try and check" approach in design for variable loading. In this way the best solutions of many practical problems in service of machinery and structures have been found, enabling an unpredictable development in engineering. It is to have in mind that the fatigue failure problem is still dominant in service of almost all structures. This indicates that the theoretical explanation of fatigue damage is far from being completely documented, even more pronounced in LCF, and probably much more in ULCF. Extension of experience gathered with fatigue failures to very complex seismic loading requires to better understand the different effects occurring when analysing variable load.

There are many effects contributing to low cycle fatigue. One of them, stress concentration caused by geometry of the component, is of special importance for fatigue crack initiation and propagation in LCF. It is clear that the stress concentration is also important for ULCF.

Many questions request a proper answer in this regard. Some of them, probably the most important for the application in ULCF, are well defined in Ref. /3/, and for that are presented here in order to explain the principle of applied approach in solving earthquake effects. For that, two introductory paragraphs, /3/, cited here, are of direct importance for the considered problem.

"What is fatigue damage? How, when and where is it accumulated? Can damage be quantified with accuracy, especially for realistic loading conditions that apply to components and structures, made from a wide variety of engineering materials?

These critical questions have been explored for more than a century and yet misleading paths, together with misconceptions about the nature of fatigue, and finally some false conclusions abound in the literature. These aspects require to be eliminated if progress in our understanding of fatigue damage accumulation is to be made."

The importance of stress concentration for fatigue damage is well illustrated in the performed experiments using specimens made of steel, /3/. On plain shaped (smooth) specimens (Fig. 1) at the central part (ø8), holes of very small size (Fig. 2) are machined. Three hole diameters and depths d were applied: 40; 100 and 200 μm, with final cone angle $\theta$ between 90 and 120°. The specimens, so machined, together with smooth specimens, were exposed to variable loading, sufficient to produce the constant nominal stress range, $\sigma = \pm510$ MPa, and corresponding amplitude of plastic strain range, $\Delta\varepsilon_p = 0.034$.
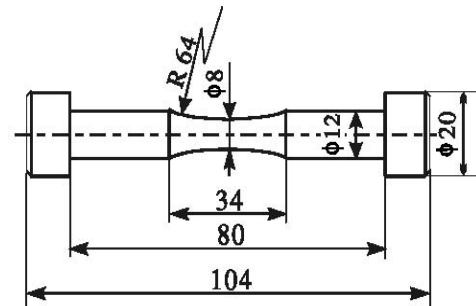


Figure 1. Shape and dimension (in mm) of specimen, tested in low cycle fatigue, /3/, with hole drilled at the centre, see Fig. 2.
Slika 3. Oblik i dimenzije (mm) epruvete ispitivane niskocikličnim zamorom, /3/, sa ubušenom rupom u sredini, vidi sl. 2
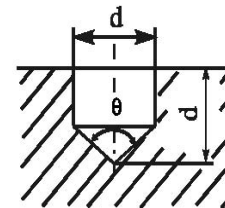


Figure 2. Geometry of drilled hole (Fig. 1).
Slika 2. Geometrija ubušene rupe (sl. 1)

The development of plastic strain and fatigue crack initiation and growth in specimens containing the hole is presented in Fig. 3. The number of cycles till fracture is the greatest ($N_f = 556$) for minimal hole diameter (d = 40 μm), for d = 100 μm, $N_f = 377$ cycles, and for the largest diameter (d = 200 μm), $N_f = 216$ cycles. The development of plastic deformation and crack extension is in Fig. 3 presented after 361 cycles for the smallest diameter, after 188 cycles for diameter of medium size, and after 94 cycles for the largest hole. It is possible to conclude that the most expressed plastic deformation corresponds to the largest hole diameter, the crack growth is the fastest in that case, and final fracture occurred after minimal number of cycles.

The first successful model for Low Cycle Fatigue, Manson-Coffin law (1954), relates the number of cycles to failure $N_f$ with plastic strain amplitude $\Delta\varepsilon_p$ by involved material constants in the form, /4, 5/:

$$\Delta\varepsilon_p N_f^{\alpha} = C_1 \qquad (1)$$

where $a$ and $C_1$ are material constants.

This is depicted, for performed experiment, presented in Fig. 4, with derived relationships according to Manson-Coffin law in log–log scale as linear dependence. The effect of stress concentration produced by the hole is clearly recognized, as well as the importance of specimen smooth surface, for which the largest fatigue life is obtained in the experiment. High surface quality can contribute significantly to fatigue life extension.



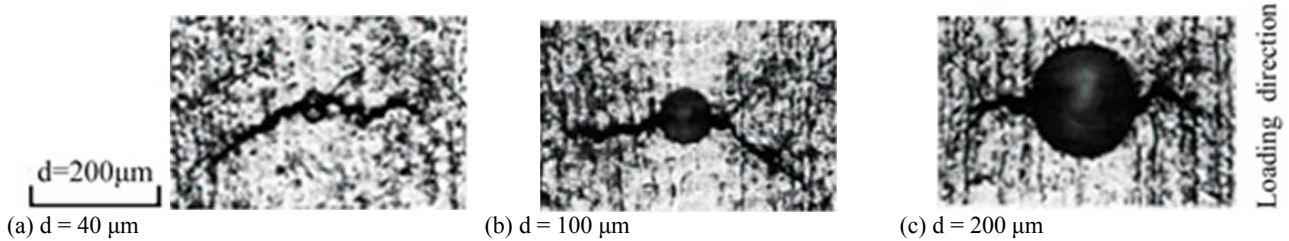(a) d = 40 μm            (b) d = 100 μm            (c) d = 200 μm

Figure 3. Different forms of fatigue crack initiation for different diameters of pre-drilled holes, /3/.
Slika 3. Različiti oblici inicijacije zamorne prsline za različite prečnike prethodno zabušene rupe /3/
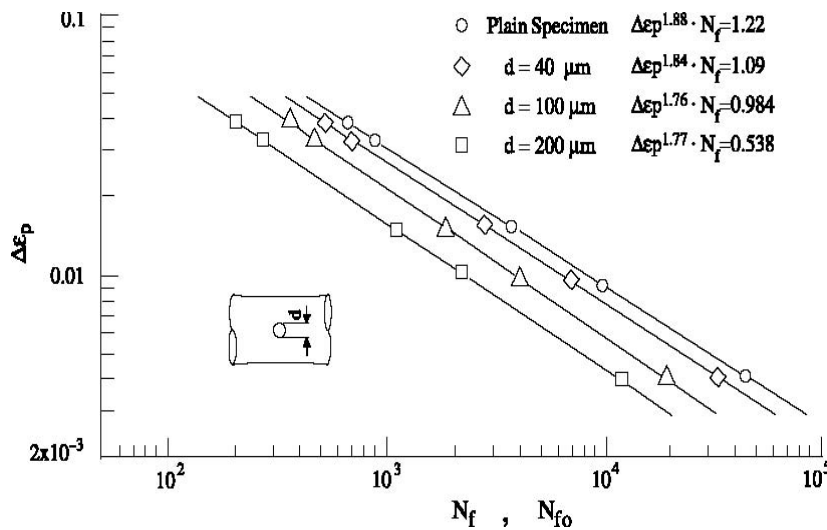


| | | |
|---|---|---|
| ○ | Plain Specimen | $\Delta\varepsilon_p^{1.88} \cdot N_f = 1.22$ |
| ◇ | d = 40 μm | $\Delta\varepsilon_p^{1.84} \cdot N_f = 1.09$ |
| △ | d = 100 μm | $\Delta\varepsilon_p^{1.76} \cdot N_f = 0.984$ |
| □ | d = 200 μm | $\Delta\varepsilon_p^{1.77} \cdot N_f = 0.538$ |

Figure 4. Manson-Coffin relationships between cyclic plastic strain amplitude ($\Delta\varepsilon_p$) and the number of cycles to fracture ($N_f$) for smooth (plain) specimen and specimens with drilled hole of different diameter.
Slika 4. Manson-Kofin zavisnost ciklične amplitude plastične deformacije deformacije ($\Delta\varepsilon_p$) i broja ciklusa do loma ($N_f$) za glatku epruvetu i epruveta sa zabušenim rupama različitog prečnika

EFFECT OF HYSTERESIS IN LOW CYCLE FATIGUE

The hysteresis effect is very important for low cycle fatigue. It belongs to non-geometrical parameters and can help to understand engineering material response to variable loading ended by fatigue in a nominally elastic range. This phenomenon, presented as the relationship stress $\sigma$ vs. strain $\varepsilon$ in Fig. 5, is known as Bauschinger's effect.

In the LCF some extent of plastic yielding will take place and the shape of hysteresis diagram, given in Fig. 6 as stress $\sigma$ normalized by yield stress $\sigma_Y$ vs. strain $\varepsilon$ normalized by yield strain $\varepsilon_Y$ is different from that for elastic load.
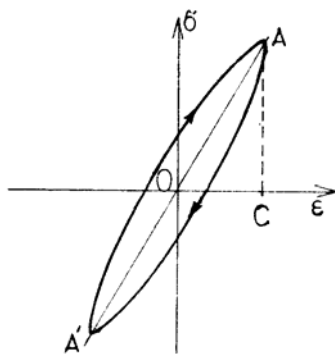


Figure 5. Hysteresis diagram – stress $\sigma$ vs. strain $\varepsilon$ relationship, i.e. Bauschinger's effect, occurred for variable reversible loading.
Slika 5. Dijagram histerezisa, zavisnost napona $\sigma$ i deformacije $\varepsilon$, tj. Baušingerov efekt pri promenljivom reverzibilnom opterećenju
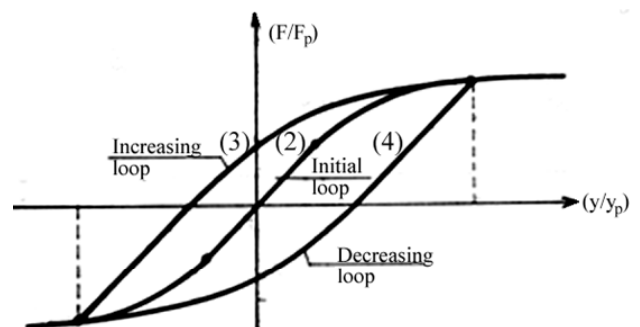


Figure 6. First hysteresis loop after plastic yielding, expressed as stress $\sigma$ normalized by yield stress $\sigma_Y$ vs. strain $\varepsilon$ normalized by yield strain $\varepsilon_Y$. Numbers (2), (3) and (4) indicate the formulae given in the text.
Slika 6. Prva petlja histerezisa posle plastičnog tečenja, izražena preko zavisnosti napona $\sigma$ normalizovanog naponom tečenja $\sigma_Y$ od deformacije $\varepsilon$ normalizovane deformacijom tečenja $\varepsilon_Y$. Brojevi (2), (3) i (4) označavaju jednačine date u tekstu

Transition from elastic to plastic range in initial tensile part, preceding to LCF sequence, is different for different materials. Three typical forms of this transition are shown in Fig. 7. They are defined by four parameters:

– stiffness ratio $k$ in initial elastic loading range and of the same value in unloading process;
– stiffness ratio $k_p$ in plastic range, after yielding;
– level of *yield* stress; and
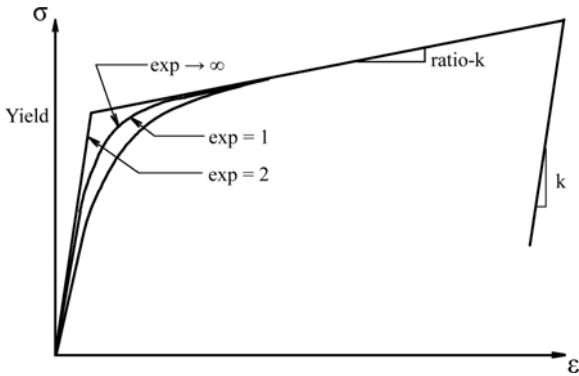– exponents defining three typical shapes – *exp*.



Figure 7. Three typical transition forms from elastic to plastic range in initial tensile part of loading, after yielding and in the unloading process.

Slika 7. Tri tipična oblika prelaza od elastičnog u plastično područje u prvom opterećenju zatezanjem, posle tečenja, i u procesu rasterećenja

For LCF testing a sequence of hysteretic loops will take place, as shown in Fig. 8, /6, 7, 8/. The shape of diagram depends on cyclic plastic strain amplitude, $\Delta\varepsilon_p$, (accumulated strain) and $N_f$, number of cycles to failure.

Material behaviour presented in Figs. 6-8 can be in convenient form described by Ramberg-Osgood relation:

$$\frac{\varepsilon}{\varepsilon_Y} = \frac{\sigma}{\sigma_Y}\left[1 + \alpha\left(\frac{\sigma}{\sigma_Y}\right)^{r-1}\right] \text{ initial part} \qquad (2)$$

$$\frac{\varepsilon - \varepsilon_1}{\varepsilon_Y} = \frac{\sigma - \sigma_i}{\sigma_Y}\left[1 + \alpha\left(\frac{\sigma - \sigma_i}{\sigma_Y}\right)^{r-1}\right] \text{ increasing loop part} \quad (3)$$

$$\frac{\varepsilon + \varepsilon_1}{\varepsilon_Y} = \frac{\sigma + \sigma_i}{2\sigma_Y}\left[1 + \alpha\left(\frac{\sigma + \sigma_i}{2\sigma_Y}\right)^{r}\right] \text{ decreasing loop part} \quad (4)$$

where $\varepsilon$ is applied strain, $\varepsilon_Y$–yielding strain, $\varepsilon_1$–accumulated plastic strain, $\sigma$–applied stress, $\sigma_Y$–yield stress, $\sigma_i$–plastic stress, $\alpha$–parameter, $r$–odd integer ($> 1$).

These relations are in low cycle fatigue valid only for relatively small displacements and high number cycles.

Low cycle fatigue behaviour will be described using a plot obtained in testing of damper "Bridge", as presented in Fig. 8, /6, 7, 8/. Four different phases, recognised in the diagram obtained in the low cycle test, can be separated.
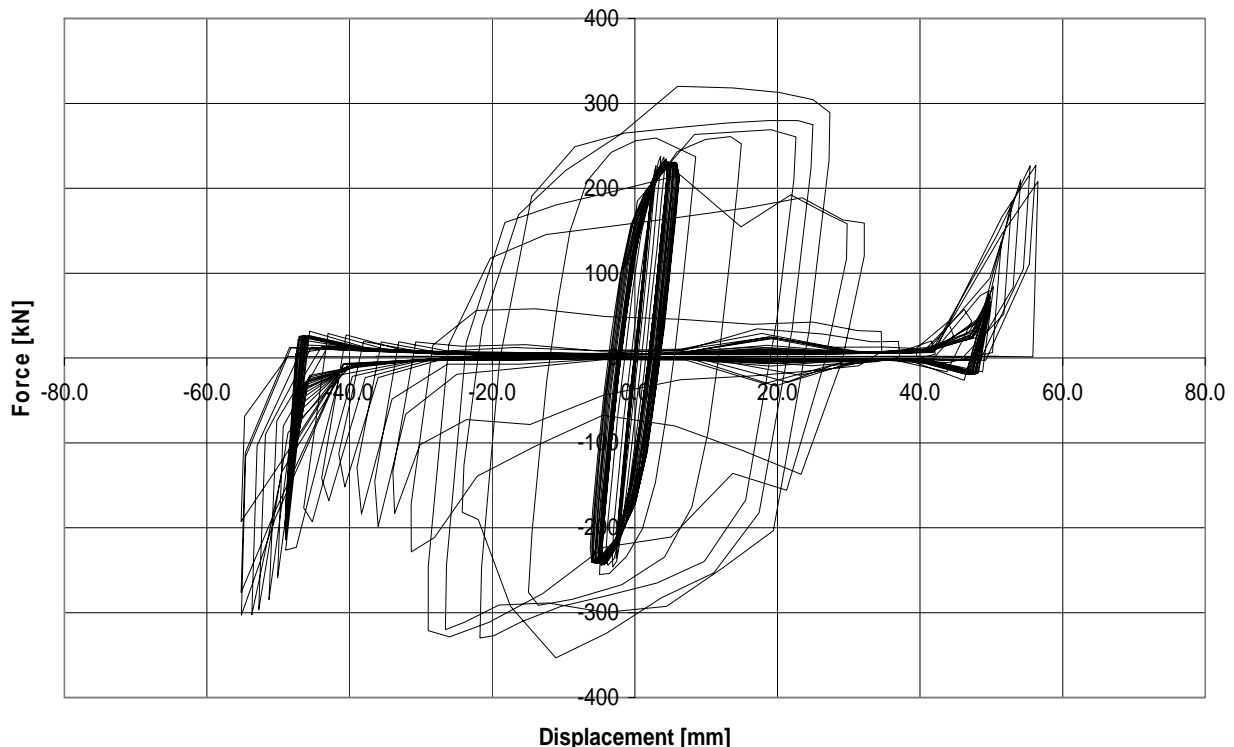


**Displacement [mm]**

Figure 8. A sequence of hysteresis loops experienced in low cycle fatigue testing, /6, 7, 8/.
Slika 8. Redosled petlji histerezisa u ispitivanju nisko cikličnog zamora, /6, 7, 8/

First phase (1) belongs to high cycle fatigue due to elastic stress bellow yield stress, $\sigma_Y$, with elastic displacement and strain $\varepsilon$. This high cycle behaviour has been exhibited in only low number of initial cycles, from 1 to 31, as presented in Fig. 9 in a form extracted from Fig. 8.

Second phase (2) includes cycles 32 to 46 at the stress level slightly above yield stress, $\sigma_Y$, in a low cycle fatigue range, extracted as damper functional segment in Fig. 10. Two first cycles of extended displacements are attributed to high seismic load and expressed local stress concentration,

probably caused by some defect, with corresponding plastic displacements and strains. However, blunting process at initiated crack tip could arrest next crack growth and return the fatigue process in regular scheme.

Third phase (3), presented in Fig. 11 as extracted from Fig. 8, took place at very high loads, at stresses close to ultimate tensile strength, $\sigma_m$. In this phase expected significant displacement and deformation have to be prevented by controlled strains in the damper and local instability (buckling) of cylindrical cover. This can be achieved by damper, designed to accept earthquake energy by developed local plastic deformation in its elements. Damper has to perform its function only in strain control, limited to 5–10%, which means the energy will be released only in a damper. This is in fact plastic collapse of the system, concentrated only in damper metallic components, but with no object failure.

Fourth phase (4), presented in Fig. 11 as extracted from the complete behaviour given in Fig. 8, indicates post

collapse situation after stress relaxation. According to Fig. 7, plastic deformation during reloading will develop at low stress level before it reaches the previously developed level, and stress will be increased after definite plastic deformation is achieved. To assure this, some components of damper structures should be designed enabling displacement control by diagonals loaded in elastic range. Due to stability loss of diagonal or fatigue development, final failure can not be completely excluded in this phase.

For consideration in ULCF, two basic approaches could be derived from the analysis of LCF. First one is hysteresis loop, Fig. 8, a measure of spent energy and achieved level of plastic deformation in successive cycle. The second, Fig. 9, indicates that the attention must be paid to the very low cycles, since the scatter from accepted empirical formulae is clear and can affect the results and derived conclusion.
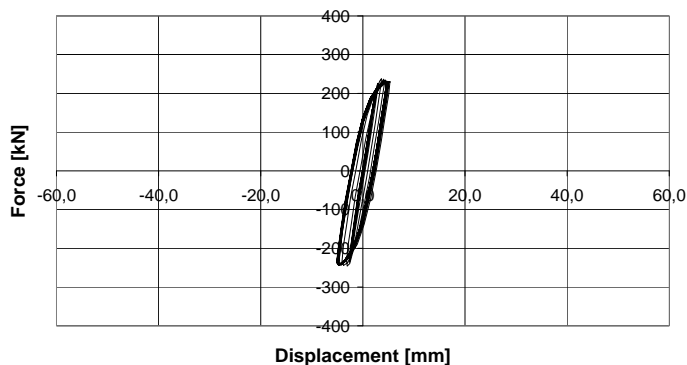


Figure 9. The phase of damper function under high cycle fatigue regime (cycles 1–31).
Slika 9. Faza funkcionisanja dampera u režimu visoko cikličnog zamora (ciklusi 1–31)
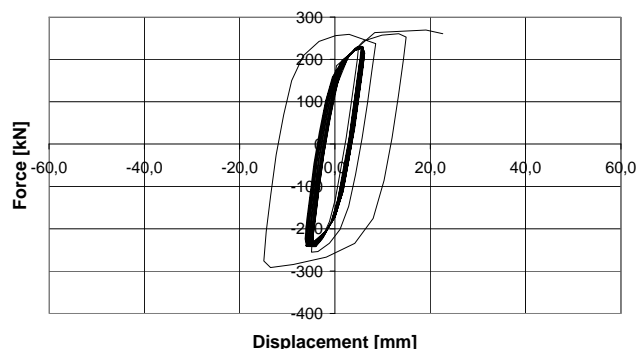


Figure 10. Initial phase of low cycle fatigue at the stress slightly above yield stress, with exaggerated displacement (cycles 32–46).
Slika 10. Početna faza nisko cikličnog zamora pri naponu nešto višeg od napona tečenja, sa izraženim pomeranjem (ciklusi 32–46)
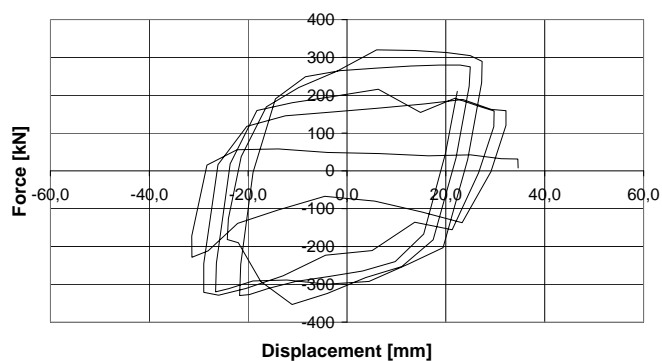


Figure 11. Excessive deformation developed in damper at high strength level by low cycle fatigue, preventing the failure of protected object by damper function (cycles 47–51).
Slika 11. Velika deformacija razvijena u damperu niskocikličnim zamorom pri naponu visokog nivoa, koja sprečava havariju zaštićenog objekta funkcijom dampera (ciklusi 47–51)
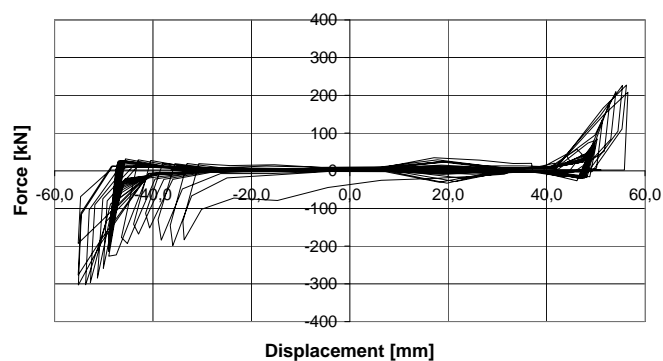


Figure 12. A sequence of hysteresis loops experienced in low cycle fatigue testing for post collapse situation after stress relaxation, exhibited during reloading (cycles 51–79).
Slika 12. Redosled petlji histerezisa razvijenih u ispitivanju nisko-cikličnog zamora u situaciji posle kolapsa i relaksacije napona, koje se javljaju tokom ponovnog opterećenja (ciklusi 51–79)

Two problems have to be accounted for when designing dampers: (1) to accept the shock loading during the earthquake, and (2) to adopt the design to the variable loading expressed during very low number of cycles. The properties of dampers in that sense have to be experimentally proved.

As it is possible to conclude from Manson-Coffin law, Eq. (1), the response of metallic material to fatigue load

depends on the level of plastic strain amplitude, $\Delta\varepsilon_p$, and provides good results for number of stress cycles in LCF higher than about 100, Fig. 13. However, in the case of ultra low number of cycles and high level of accumulated strain the difference between experimental results and values calculated by Eq. (1) is clearly expressed, indicating that Manson-Coffin law can not be directly applied to ULCF.
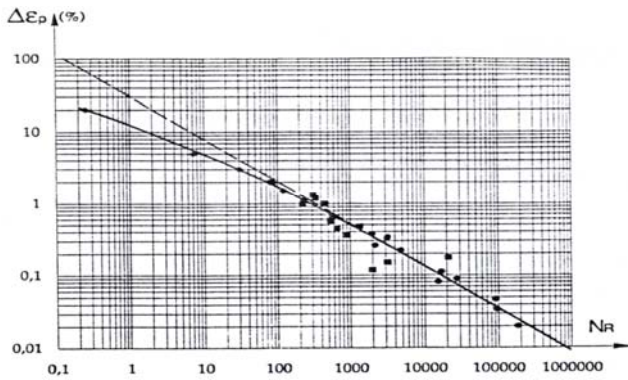
Figure 13. Number of cycles $N_R$ vs. plastic strain $\Delta\varepsilon_p$ in low cycle fatigue: experiment (dots) and fit curve (solid line), compared to Manson-Coffin law (dashed line).

Slika 13. Zavisnost broja ciklusa $N_R$ i plastične deformacije $\Delta\varepsilon_p$ pri niskocikličnom zamoru: eksperiment (tačke) i fitovana kriva (puna linija), poređana sa Manson-Kofin zakonom (crtkana linija).

## PATENTED DESIGN OF DC 90 SYSTEM

System DC 90 for seismic strengthening of building structures, based on previously described experience, experimental testing and theoretical background of low cycle fatigue, is accepted as a patent /9/. Short presentation, given here, is based on this patent. DC 90 system consists of elements (Fig. 14), that include trusses/vertical elements (3), transverses/diagonal elements (4), dampers/absorbers (5) and foundation collars (2), distributed around perimeter of the building (1), and which provide the building with toughness and stiffness, even in the case of the highest seismic shocks. The system through the rigid mezzanine floor level plates transmits the horizontal seismic forces to individual system elements and thus transmits seismic forces throughout base foundation collars further into the ground.

In the International patent classification (MKP), this invention has designation mark E04 G13/04.

The technical problem is connected by the nature of the construction of buildings that are massive, heavy and rigid. In the moment of seismic shock they are exposed to high forces capable to cause huge damage. The proposed new system involves resilience and controls, deformations and dynamic characteristics, enabling the system to accept most critical seismic shocks, since civil engineering constructions with the reinforced concrete beams (wall reinforced), building of reinforced concrete walls and various injections are vulnerable in the case of earthquake.

The essence of the invention is that this new construction is an implanted replacing function of the existing breakable and massive masonry construction, enabling the resilience and controls of deformations, so that it increases seismic resistance of the entire construction system. The most important component of the system is a damper (absorber).

The detailed description of the damper is hereby defined in Fig. 15.

The components of the system are the elements at both ends of the diagonals (7) and (6), element for dissipation of seismic force energy (10), the newly applied steel "ring" at the perimeter of the building (9), and the covering element made of steel (8).
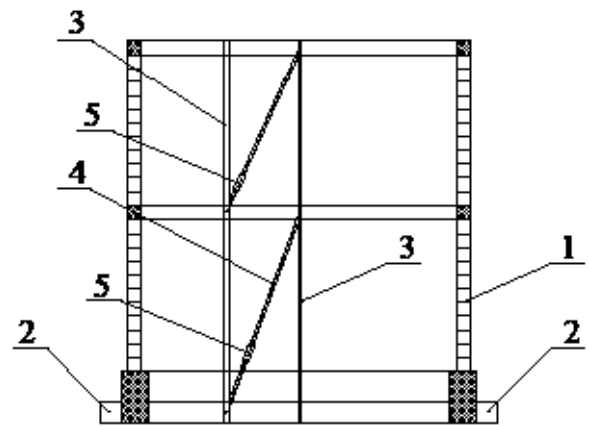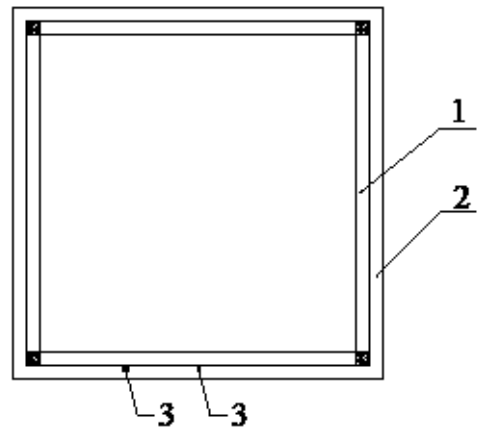


Figure 14. Disposition of DC 90 system components on a damaged object construction in its base and cross section.

Slika 14. Raspored komponenti DC 90 sistema na konstrukciji oštećenog objekta u njegovoj osnovi i poprečnom preseku
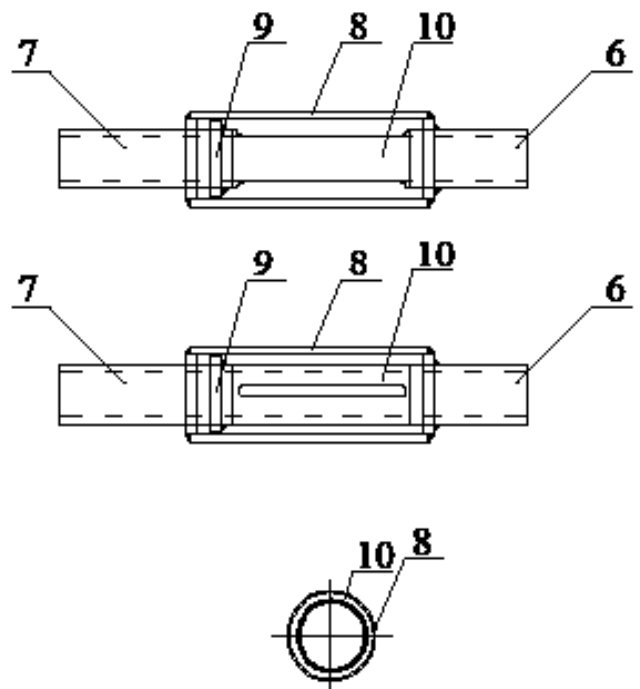


Figure 15. Design scheme of the damper for acceptance of seismic load energy in longitudinal and cross sections.

Slika 15. Šema projekta dampera za prihvatanje energije seizmičkog opterećenja u uzdužnom i poprečnom preseku

With this last element (8) the exact load can be assessed at the moment when the extended deformation is achieved. By calibrating the distance between wrist-enhancement of the left ring at the element (8) and stand-off insulator (regulates distances) and the ring (9), the displacement can be regulated, by which virtue the dampers absorber realizes its intended function.

Following the drawing given in Fig. 14, the construction for seismic strengthening of masonry structures wall (1), built out of dry brick, solid or honeycomb or throughout by reinforced concrete (RC) rigid floor plates, or indeed by the flexible structure by stiffening with special stretchers or by bracing with the new lightweight concrete floor plate to the existing building's structural wood beams, and by which the foundation are also reinforced by RC collars (2) from outside of the structure, indicated that, vertical excitation – seismic reinforcements (3; 4; 5) are uniformly placed around the perimeter of the existing construction, and consist of vertical trusses/new columns (3), transverses/diagonals of steel pipes (4) and dumpers (5) which are placed at the bottom of the steel diagonal at the exact place of the conjunction between diagonal truss and horizontal beam joint, all done by using screws.

According to the requested design, as presented in Fig. 15, of construction for seismic strengthening of the structure (1 in Fig. 4) indicated by the virtue of the absorber of seismic energy (5) which consists of parts of diagonal of steel pipes (6) and (7) that are joined together by welding the horizontal node and the transverse diagonal (4, Fig. 14) within the area of the vertical reinforcement stretcher, and should be noted that between them is now placed a new element for energy dissipation and elastic-plastic nature of performance (10), made of steel pipes that have a lesser cross-section area than the cross-section areas of elements (6) and (7), or they can be reduced with holes / bull's eyes (by reducing cross-section area) and whose deformation is controlled by the distance control element (9) and the element for the enhancement (8), all depending on mutual longitudinal distance of these two elements.

DESIGN, TESTING AND APPLICATION OF DAMPERS

Considering actual objects to be strengthened the dampers of different designs for different applications are developed, manufactured and tested, /8/. Typical solutions are presented here and their applications discussed.

*Damper "Bridge" – design and testing*

The request to control displacements of high level and to accept high loads typical for bridge structures could be fulfilled by a new design of a damper. The damper is designed to be applied in the upper part of bridge columns and to join main bridge girders to the columns (lower alignment).

Verification of accomplished design requirements was done through extended testing performed at the Military Technical Institute (VTI) in Belgrade. Damper for bridge application, displacement 100 mm, is shown in Fig. 16, and the test preparation on servo hydraulic closed loop system MTS is presented in Fig. 17, /6/. Tests were performed by quasi-static loading in displacement control and by variable loading in frequency control and in strain control.



Figure 16. Typical damper for bridge application, tested at VTI.
Slika 16. Tip dampera za primenu na mostu, ispitan u VTI



Figure 17. Testing of one sample of damper "Bridge", nominal length $l = 1000$ mm, at Military Technical Institute (VTI).
Slika 17. Ispitivanje uzorka dampera „Most" nazivne dužine $l = 1000$ mm u Vojnotehničkom institutu (VTI)

General view of obtained results is given in diagram (Fig. 8), and typical sequences are extracted in Figs. 9–12. In order to better understand damper response to applied load and types of hystereses that occurred during the test with increasing number of cycles, the change of the number of cycles with force is presented in Fig. 18, and with the displacement in Fig. 19, and with dissipated energy in Fig. 20.

A very important result obtained in the performed test is that low cycle fatigue is a complex phenomenon, affecting through series of influencing factors that determine the type of experienced fatigue mode. The correspondence between acting load, registered displacement and consumed energy with the range of deformation (elastic, plastic) and the shape of hysteresis loop is obvious. In case of 1 to 31 cycles (Fig. 9), dominant high cycle fatigue is confirmed by the quasi-static character of force, increasing at first and then being constant, (Fig. 18), negligible displacement (Fig. 19), and only with the elastic energy involved, except for the

last few cycles (Fig. 20). Small peaks in force in cycles 31–32 were sufficient to produce increased displacements and corresponding energy consumption for plastic deformation, but after developed eventual local plastic deformation, fatigue had continued to develop uniformly (Fig. 10). Real low cycle fatigue took place for loads producing stress between the yield and ultimate tensile strength of material, followed by high displacements and plastic deformation, and requiring increased energy dissipation, Fig. 11. The situation in Fig. 12 can be considered as a reloading sequence, after stress relaxation.
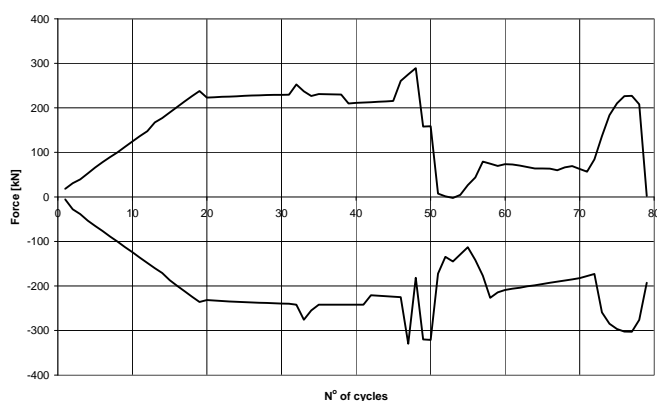


Figure 18. Force vs. number of cycles, damper "Bridge".
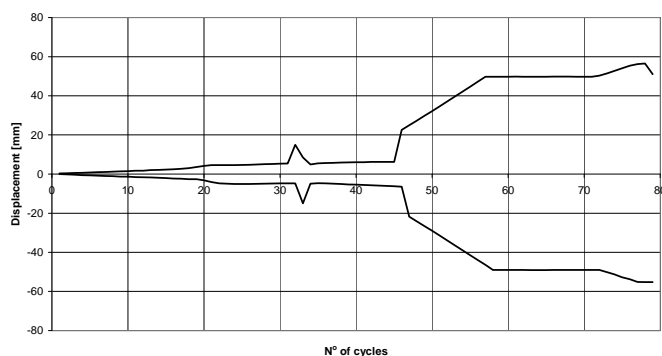Slika 18. Promena sile sa brojem ciklusa, damper „Most"



Figure 19. Displacement vs. number of cycles, damper "Bridge".
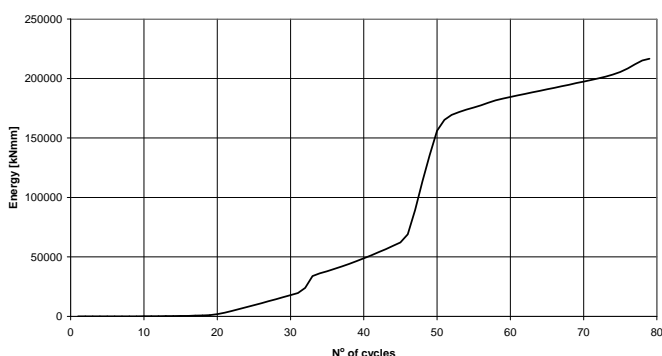Slika 19. Promena pomeranja sa brojem ciklusa, damper „Most"



Figure 20. Energy vs. number of cycles, damper "Bridge".
Slika 20. Promena energije sa brojem ciklusa, damper „Most"

However, the applied load in the test is mainly uniform, and different from real loading in the earthquake event.

This fact must be respected in design, manufacturing, and application of dampers. The analysis of performed tests has revealed some cognitions which could be important for

further improvement in the damper design. No one tested sample has fractured in brittle manner, regardless of the different frequencies applied (1–10 Hz) and different displacement levels in the tests. The selected material behaved in a proper way, without failure or unexpected damage. Also the welded joints, which may be critical in this regard due to possible defects, heterogeneity in microstructure and mechanical properties did not fail. Since the response of the damper was affirmative, it is possible to conclude that all phases of manufacture, including welding were at the required level. Additional contribution to safe operation is attributed to the introduced rings, produced of lead, which enabled uniform distribution of external load to the circular damper components.

In the performed tests, about 1000 cycles were necessary for failure to occur. It is also found that the post collapse capacity of dampers is high (Figs. 8 and 12). However, in an average earthquake and average amplification, the number of cycles in low cycle fatigue is 5 to 10 times lower that assessed in the performed investigation.

It is also interesting to notice, as expected, that with increased load or displacement the number of cycles to failure will be reduced, and for controlled fixed displacement in the material by increasing number of cycles, load will decrease.

*Damper "Mionica" – design, testing and application*

This type of damper is developed for the application in the Kolubara region in Serbia, which is sensitive to earthquake. In 1998, a strong earthquake destroyed residential buildings, /10/. DC 90 system™ has designed a new damper type and applied it on several buildings, or damaged ones, thus retrofitting and giving protecting in an eventual earthquake shock.

Characteristics of objects in the Kolubara region

Residential objects are produced of bricks (plain or gitter, burned or dried) or stone. The cementing material for these materials was extended lime mortar. New objects are built using horizontal and vertical serclages and TM multi-floor structures, whereas old objects, built with no serclage, are typical for their flexible ceilings. These ceilings have not requested stiffness in their own plane and are not properly connected with the walls. Frequently, gabled roofs are not stiffened.

Masonry structures are very sensitive to earthquake activity. It is well known that those structures have large mass, and consequently, because of bad cohesion between bricks (stones) and mortar, they crack and suffer damage when exposed to earthquakes, so they cannot avoid a non-linear post elastic condition.

Large masses of constructed objects, predominantly built with required resistance to uniaxial compressive strength only, are typical for the Kolubara region. Their tensile loading capacity is low, as well as the resistance to fatigue. Since the applied structural materials in these buildings are brittle, their ductility and toughness are poor.

Properties of acting seismic loading and caused damages

The intensity of a strong earthquake experienced in 1998 was 5.3 on the Richter scale, followed by several after-

shocks of lower intensity, /10/. Distribution of frequency was different, basic frequency being 3.2 Hz, close to the frequency of damaged objects constructed in the region. After dozen of prelusive shocks, the main shock followed with five times higher acceleration. During the next few days, in the relaxing period, at least 100 shocks of reduced intensity repeated, contributing to additional damages in the already deteriorated objects.

During this earthquake, mostly damaged were residential objects. Clearly expressed diagonal cracks on old buildings are caused by exceeded critical shear stress (Fig. 21). Significant deformations and cracks occurred on non-stiffened gabled roofs. Damages were found on new objects, with horizontal and vertical serclages and TM structures.



Figure 21. Example of damaged building in the Kolubara region.
Slika 21. Primeri oštećene zgrade u području Kolubare

Design requirements for damper

The natural requirement was to build-in an element in the building structure (Figs. 14 and 15), capable to involve toughness and ductility in a structure. Such an element should be developed based on investigation and experiments. Damaged buildings have to be equipped with new elements in the scope of vertical stiffeners, and in new buildings they can be applied as a component of diagonal elements.

The new damper DC 90 should be applied in elements (vertical and diagonal) for vertical strengthening. In dynamic loading by controlled fatigue, the location of plastic hinge is determined, the time of appearance and intensity of load and displacement also, enabling proper building behaviour in seismic conditions. The damper operates in the elastic-plastic range, and controls the maximum displacement for designed load capacity. In the post-collapse period it limits displacement. Fracture is directed to the diagonal (due to overload or element stability loss in compression), since the damper capacity is higher.

Design peculiarities, manufacture and testing of dampers

System DC 90 comprises a number of structural elements which strengthen brittle walls and make them tougher, and also make floor slabs and ceilings stiff and capable to transmit the load in their own plane. The system integrates foundations, connects them by foundation collars, and makes them stronger to accept horizontal displacements and high vertical loads.

The testing phase of an original state and strengthened building by applying the DV 90 system, based on the scheme presented in Figs. 14 and 15, is presented in Fig. 22.

Vertical elements, walls, are strengthened by vertical stiffening elements that connect horizontal slabs and the foundation. Vertical stiffening elements (bars) consist of pre-stressed vertical ties, while the other elements of the bars are diagonals with the damper, seismic energy absorber and horizontals as parts of stiff floor slabs. So the strengthened wall structure becomes ductile and capable to accept alternative horizontal dynamic displacements.

Horizontal elements are not stiff in their own plane, floor slabs and ceilings are strengthened by impregnation with a thin, lightly reinforced, concrete slab, or by involved horizontal bracings, connected with vertical stiffening elements.

The foundation structure is confined with the collar, joined by anchors, with anchored applied vertical stiffening elements.

A general view of damper Mionica is shown in Fig. 23, and as an illustration of welding joints, its longitudinal section is given in Fig. 24. The damper main part is produced from pipes 48.3 mm in diameter, wall thickness 3 mm, designed to accept loads of 110 kN.



Figure 22. Experimental testing of building (left – original, right – strengthened).
Slika 22. Eksperimentalno ispitivanje zgrada (levo – prvobitna izvedba, desno – ojačana)

Figure 23. The general view of Mionica type damper.
Slika 23. Opšti izgled dampera tipa Mionica



Figure 24. Longitudinal section of damper welded structure.
Slika 24. Uzdužni presek zavarene konstrukcije dampera

The damper is produced of pipe elements (1), (2) and (3), of dimensions given in Fig. 25. The applied material is steel of yield strength 600 MPa, ultimate tensile strength 700 MPa, and elongation at fracture up to 22%, sufficiently

strong for the expected load, and of ductility and toughness levels necessary to accept expected earthquake energy.

The design of the damper consists of a central part known as the "dog bone" due to its shape, and is very fine machined in order to avoid appearance of notches and cracks that may cause stress concentrations and reduce fatigue life. Displacement can be controlled by one adjustable– and three fixed rings, assuring a dilatation of required length for desired low cycle fatigue, caused by seismic loading, and the load intensity will be controlled by the cross section reduction due to plastic deformation.

A drawing scheme of Mionica damper is presented in Fig. 25, together with the basic hysteresis loop, /7/.

For proper damper design it was necessary to analyse the parameters describing fatigue behaviour. Special importance in the structural integrity of the new dampers are diagonal elements, aimed to accept shear stresses.

Basic design requirements for the "Mionica" damper are as follows:

– reduction of diameter, minimum 20%,
– length reduction enabling strains up to 10%,
– high surface quality of the element "dog bone" type, with prescribed level of surface roughness,
– elements for local and global buckling are involved, capable to be used in compression (concrete, lead, aluminium plate, and elements for sliding),
– material constants $a$ and $C_1$ in Eq. (1), and other damper constants had to be specified,
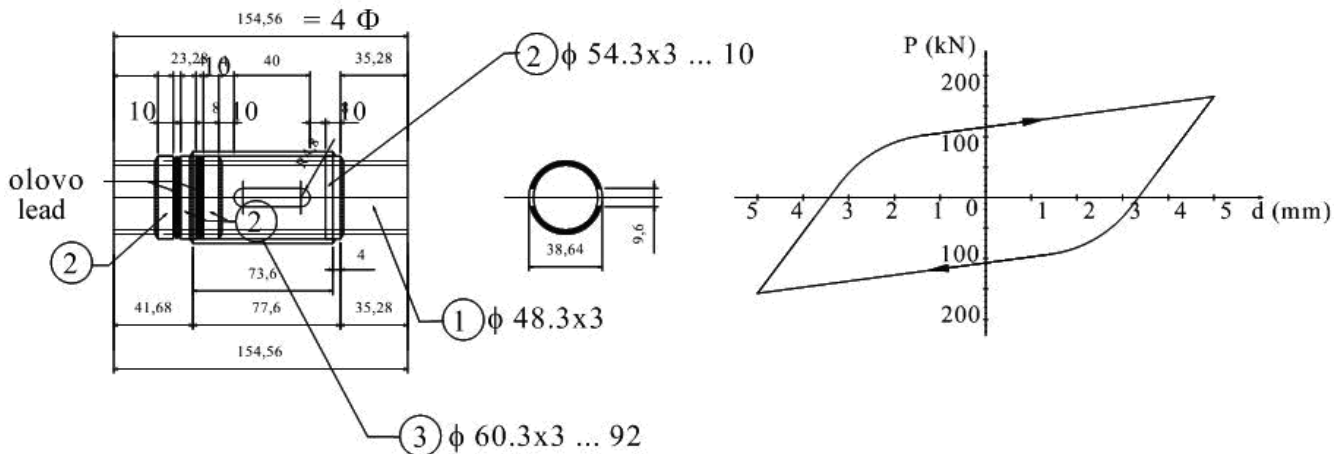– strain rate should be specified.



Figure 25. Design of the damper type "Mionica" with basic hysteresis loop.
Slika 25. Konstrukcija dampera tipa „Mionica" sa osnovnom petljom histerezisa

The first hysteresis loop, obtained experimentally, is shown in Fig. 25. A complete picture of the hysteretic behaviour of damper "Mionica" in LCF, obtained experimentally, is shown in Fig. 26.

The change of force, displacement and energy by number of cycles during low cycle fatigue of damper "Mionica" is presented in Figs. 27, 28 and 29, respectively.

Low cycle fatigue experiments of damper can deliver the data, necessary for the Manson-Coffin law, Eq. (1), which should also be considered and analysed for an ULCF situation, typical for earthquake loads. This data includes cyclic plastic strain range (accumulated strain), $\Delta\varepsilon_p$, and number

of cycles to failure, $N_f$. The history of the accumulated strain and the level of current strain, $\varepsilon$, should also be taken into account, expressed by current dilatation, as well as the strain rate, $\varepsilon_p/t$.

Two lines (a circle and a straight line, Fig. 7) can be used to define a hysteresis diagram, $F(\sigma, \varepsilon)$, with the help of Eqs. 3 and 4.

Described relationships in Figs. 27 to 29 (and also in Figs. 18 to 20) can be connected with the development of plastic deformation, confirmed in experiments with damper "Mionica" and presented in Fig. 30.
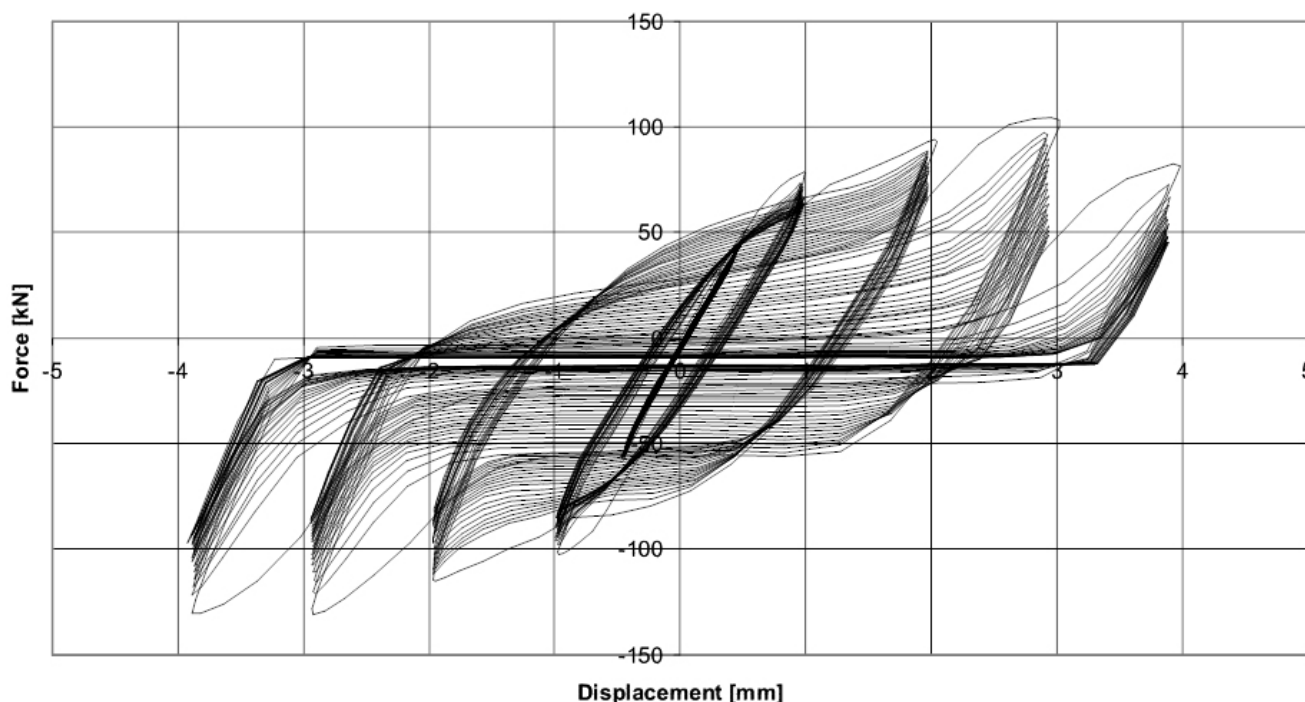
Figure 26. A sequence of hysteresis loops experienced in low cycle fatigue testing, damper "Mionica", / 7, 8/.
Slika 26. Redosled petlji histerezisa u ispitivanju niskocikličnog zamora, damper „Mionica", /7, 8/
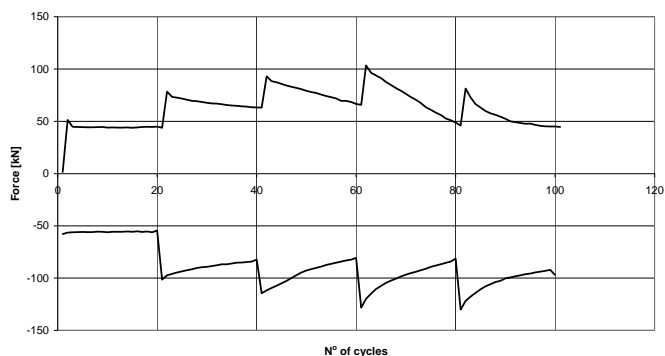


Figure 27. Force vs. number of cycles, damper "Mionica".
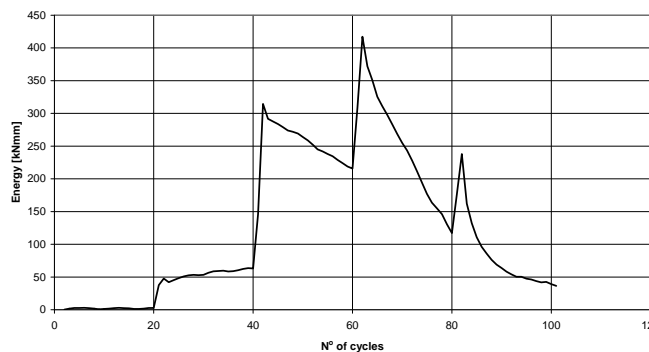Slika 27. Promena sile sa brojem ciklusa, damper „Mionica"



Figure 28. Displacement vs. number of cycles, damper "Mionica".
Slika 28. Promena pomeranja sa brojem ciklusa, damper „Mionica"



Figure 29. Energy vs. number of cycles, damper "Mionica".
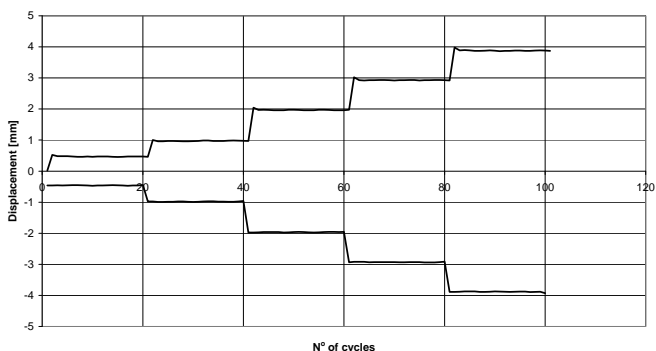Slika 29. Promena energije sa brojem ciklusa, damper „Mionica"

CONCLUSIONS

Very low cycle fatigue happens in the case of 10 to 20 cycles before rupture, followed by large plastic strain and maximum stresses that are much larger than yield stress. This case is very important for design of dampers applied for reconstruction of seismically damaged structures. From examples of laboratory experiments and in real structures it is shown that the "very low cycle fatigue concept" should be applied in the analysis of earthquake damaged structures and their reconstruction, because the Manson-Coffin law overestimates the number of cycles before failure. Earthquakes are very dangerous impacts on civil engineering structures. It is practically impossible to understand the behaviour of buildings subjected to seismic loads without essential knowledge of behaviour of structural members from the view point of the low-cycle fatigue process as well as the complete stability of the structure during all phases of earthquake activity. It is very important to determine the parameters that define the damper (diameter, percentage of

reduction, length reduction, roughness of the element "dog bone", elements for local and global buckling (for work in compression, concrete, lead, aluminium plate, and elements for sliding), and $C$ and $\gamma$ – material and damper constants.



```
PE, Max. In-Plane Principal
SNEG, (fraction = -1.0)
(Avg: 75%)
    +5.846e-02
    +5.359e-02
    +4.872e-02
    +4.385e-02
    +3.897e-02
    +3.410e-02
    +2.923e-02
    +2.436e-02
    +1.949e-02
    +1.462e-02
    +9.743e-03
    +4.872e-03
    +0.000e+00
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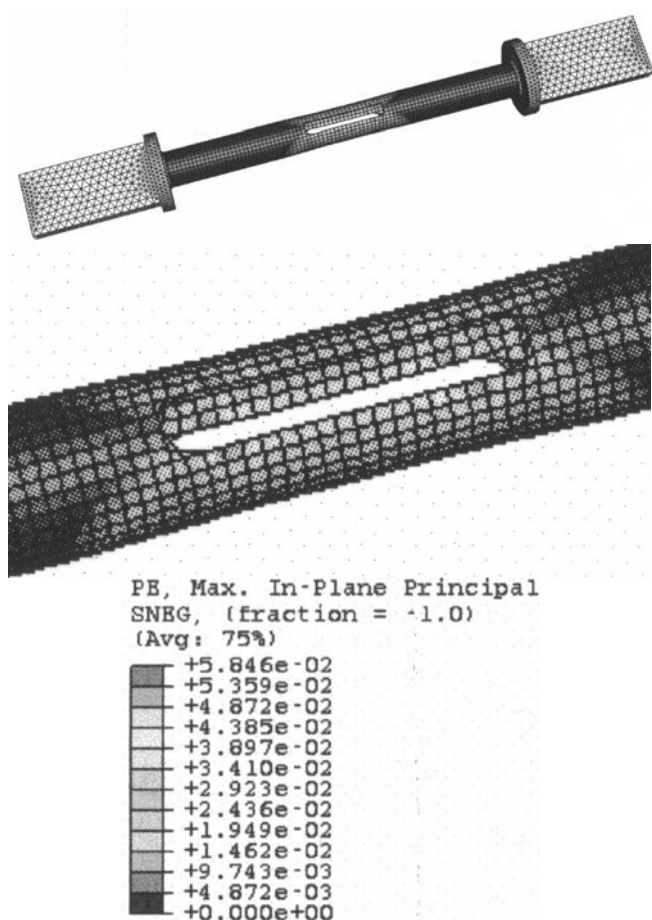
Figure 30. Plastic strain field of the pipe section corresponding to 5 mm elongation.
Slika 30. Polje plastičnih deformacija sekcije cevi koje odgovara izduženju od 5 mm

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