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LOAD MONITORING USING FIBRE OPTICAL TECHNOLOGY

PRAĆENJE OPTEREĆENJA PRIMENOM TEHNOLOGIJE OPTIČKIH VLAKANA

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Ključne reči
- vlakna sa Bragovom rešetkom
- ispitivanje konstrukcija
- senzori deformacija
- zamor

Abstract

Effective dimensioning requires an effective experimental in situ analysis of the stress states of structures. Load monitoring is the first step for the calculation of residual lifetime, respectively the structural health under realistic conditions and special loads. For many decades already, stress analysis using strain gauges has been a proven and qualified method for analysing the loading conditions in structural mechanics. Strain gauges are particularly suited for determining such mechanical loads on structures or components, because they detect minimal structural deformations. Quality and reliability of the sensors determine the durability of the structural system. Even under the background of lightweight materials, fibre optical sensors are increasingly used today, amongst others due to:

• Low weight of the sensors, cables and data acquisition unit as well as assembling work load

• Fatigue behaviour of the sensors due to applied high mechanical strain.

Basic considerations and experimental investigations on fibre optic Bragg grating strain sensors is presented and a number of measuring effects that influence the strain transformation from specimen into the fibre optic sensors are discussed. The presentation is also to enforce the discussion between experts of different subjects and areas of expertise.

Izvod

Efikasno dimenzionisanje zahteva efikasnu eksperimentalnu analizu stanja napona konstrukcije in situ. Praćenje opterećenja jeste prvi korak u proračunu preostalog radnog veka, posebno stanje konstrukcije u realnim uslovima i pod posebnim opterećenjima. Već više desetina godina, naponska analiza primenom mernih traka predstavlja dokazani i kvalifikovani postupak za analizu uslova opterećenja u mehanici konstrukcija. Merne trake su posebno pogodne za određivanje takvih mehaničkih opterećenja na konstrukcije ili komponente, jer se njima detektuju minimalne deformacije konstrukcije. Kvalitet i pouzdanost senzora određuje trajnost sistema date konstrukcije. Uprkos iskustvima sa lakim materijalima, senzori sa optičkim vlaknima se sve više upotrebljavaju danas, između ostalog i zbog:

• Male težine senzora, kablova i jedinice za prikupljanje podataka, kao i sklopa za radno opterećenje

• Ponašanje zamora senzora usled dejstva velikih mehaničkih deformacija

Data su osnovna razmatranja i eksperimentalna istraživanja senzora deformacija sa optičkim vlaknima sa Bragovom rešetkom, a i diskusija brojnih mernih uticaja na transformaciju deformacije, preko epruvete na senzor sa optičkim vlaknima. U radu se takođe podstiče diskusija među ekspertima raznih profila i oblasti proučavanja.

INTRODUCTION

For decades, strain gauges have been an effective means of implementing structural tests in selected areas, e.g., on components or functional groups, to enable expected strain gradients to be experimentally proven or assessed under real or simulated loading. The strain gauge method has proven effective in a myriad of applications. Since the measured 'strain' cannot be directly traced back to a physical quantity, experience and diligence when preparing, bonding, covering and instrumenting a strain gauge installation are prerequisite for reliable measurements, /1/. Normative guidelines for the dimensioning and use of electrical strain gauges, for example VDI/VDE 2635, /2/, or BSSM Code of practice, /3/, provide orientation. Strict control of production processes ensures that, through careful selection of strain gauges and coupling media, strain occurring in the measurement object is almost entirely transmitted onto the strain measurement foil.

On the basis of over 60 years of experience in the production and application of electrical strain gauges, HBM has developed and sold optical strain gauges, too, for several years; they offer particular benefits for the user (see Fig. 1).

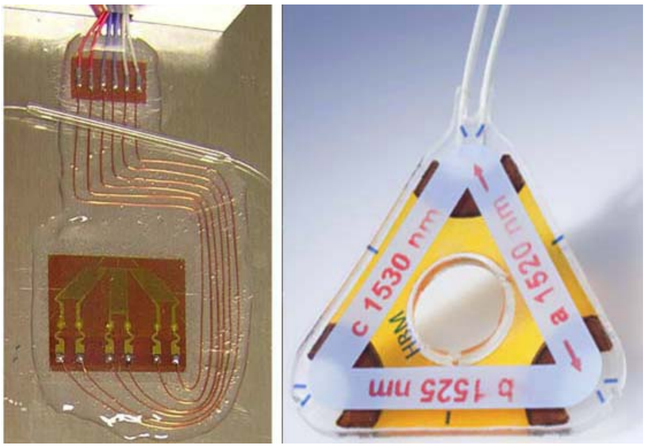

Figure 1. Electrical and optical rosette.
Slika 1. Električna i optička rozeta

Key benefits of optical strain gauge technology include:

- Reduction of wiring effort through intrinsic arrangement of sensor and information line in a single medium, the optical fibre. One fibre (chain) can accommodate many sensors.
- Insensitivity to electromagnetic interference, potential differences, and the effects of high voltage.
- Can be used in potentially explosive atmospheres – provided that diverse design criteria concerning the layout of fibre and interrogator are complied with. For example, the performance of the laser needs to be so low that, in the event of a potential fibre break, emanating radiation is below an ignition energy level, /4/.
- Fibre-optic strain gauges offer higher resistance to alternating loads than electrical strain gauges. Optical fibres have a higher damage tolerance than metals.

OPTICAL BRAGG GRATING SENSORS

Fibre-optical Bragg gratings consist of a multiplicity of formed fringes inside the optical fibre core over a length of some millimetres. Such designs of interference patterns require use of special photonic technologies in the nanoscale range to generate the lattice.

Periodic modulation of the fibre core's effective refraction index n_{eff}, enables incoming light to be filtered by this grating. Reflections of equal phase accumulate to a strong reflection peak, with Bragg wavelength λ_B. The Bragg wavelengths λ_B are chosen in compliance with telecommunications wavelengths (C-band, between 1 500 nm and 1 600 nm), where optical losses in the glass fibre are at a minimum. With the given grating length, the sensor therefore consists of more than 10 000 grating periods, /5/.

The principle of a fibre Bragg grating is illustrated in Fig. 2.

The centre wavelength of the reflected (or transmitted) peak resulting from the above described constructive interference in the grid is then analysed in a measuring system – the interrogator. This peak shifts by the fundamental relation of the uniform fibre Bragg grating

$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda \qquad (1)$$

and hence also the Bragg wavelength λ_B itself are however affected by strain and temperature on the measuring spot:

$$\lambda_B(\varepsilon,T) = 2 \cdot n_{eff}(\varepsilon,T) \cdot \Lambda(\varepsilon,T) \qquad (2)$$

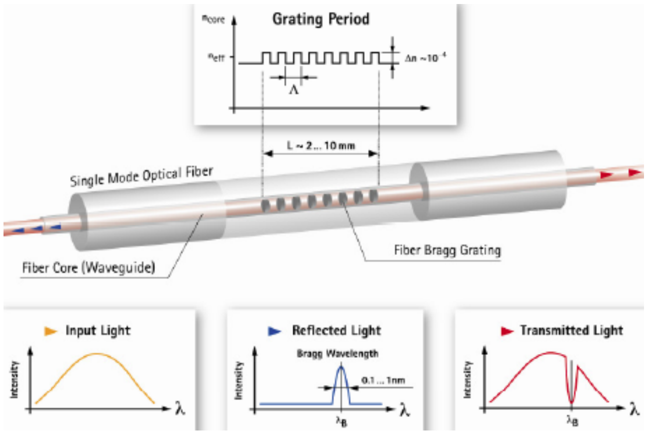

Figure 2. Principle of a fibre Bragg grating.
Slika 2. Princip vlakna sa Bragovom rešetkom

The shift of the Bragg Grating wavelength due to strain and temperature changes is given by partial differentiation of Eq.(1). Periodic spacing between the fringes and effective index of refraction are independent of each other. According to the total differential for small variations it may be written as, /6/:

$$\Delta\lambda_B = 2\left(\Lambda\frac{\partial n_{eff}}{\partial l} + n_{eff}\frac{\partial \Lambda}{\partial l}\right)\Delta l + 2\left(\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial \Lambda}{\partial T}\right)\Delta T \qquad (3)$$

In the formula, Δl stands for the effect of strain and ΔT for the effect of temperature, the magnitude of the effects is related to a set of four optical coefficients:

$$\alpha_{n\varepsilon} = \left(\frac{1}{n_{eff}}\frac{\partial n_{eff}(\varepsilon,T)}{\partial \varepsilon}\right); \quad \alpha_{\Lambda\varepsilon} = \left(\frac{1}{\Lambda}\frac{\partial \Lambda(\varepsilon,T)}{\partial \varepsilon}\right);$$

$$\alpha_{nT} = \left(\frac{1}{n_{eff}}\frac{\partial n_{eff}(\varepsilon,T)}{\partial T}\right); \quad \alpha_{\Lambda T} = \left(\frac{1}{\Lambda}\frac{\partial \Lambda(\varepsilon,T)}{\partial T}\right)$$

The photoelastic coefficient $\alpha_{n\varepsilon}$ expresses the change of the refractive index upon strain, the coefficient $\alpha_{\Lambda\varepsilon}$ describes the relative change of the Bragg grating length vs. applied elastic strain of the specimen. In experimental stress analysis the k-factor is commonly used, /7/. For strains up to 1%, the relationship between impressed strain and wavelength displacement remains linear as a first approximation, /8/. In the here discussed nominal telecommunications wavelengths range, the sensitivity of the Bragg grating is $k = 0.79$.

The thermo-optical coefficient α_{nT} expresses the thermal change of the refractive index of the germanium-doped silica fibre core, /9/, and the (longitudinal) thermal expansion coefficient $\alpha_{\Lambda T}$ represents the reversible change in length of the silica fibre with temperature. The quantity of this temperature sensitivity is approximately +10.6 pm/K, in a temperature range from ambient temperature up to 100°C.

Figure 3 shows the thermal output of fibre optical strain gauges, /10/, mounted on special panels of different materials. The thermal output of a Bragg grating mounted on aluminium is about 1 800 μm/m at 80°C, where 20°C is the reference temperature. Compensation of this temperature effect is a must in long-term (static) and quasi-static applications. In a temperature range of –20 up to 100°C, the curve is almost linear and enables compensation either with a second optical strain gauge or an independent electrical sensor like Pt100.

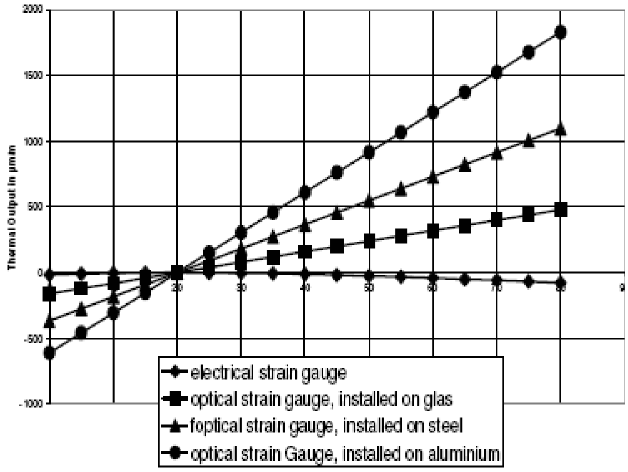

Figure 3. Comparison of temperature output signals of optical and electrical strain gauges, /10/.
Slika 3. Poređenje izlaznih temperaturskih signala optičkih i električnih mernih traka, /10/

APPLICATION ASPECTS

Fibre-optic sensing systems are highly suitable for use in configurations comprising multiple sensors or strain gauge spots in a single cable. Thus all data is transmitted in the same medium, which provides enormous economic benefits.

The application of fibre-optic measuring chains led to completely new approaches. Each measuring grid in the chain is arranged in one and the same optical fibre.

Standard solution in electrical strain gauge installations is star-topology cable distribution between the DAQ system and the individual sensors. Significant savings in labour and material costs have been achieved with decentralized and bus-controlled devices. In case of optical fibre sensors, multiplexing is an important issue, offering advanced approaches of sensor instrumentation, almost different types of strain gauges and optical transducers can be combined. The reduction of cost of optical based sensors improves the predominance against conventional electrical strain gauges and transducers.

The cable is, in many cases of long distances, in electrical installations one of the most weightily parts of the measuring system. In the case of ohmic strain gauge, it has to be adapted to voltage drop due to the power consumption as well as to noise shielding, in case of passing sources of electromagnetic noise. Where distances of kilometres without need of auxiliary devices are needed, however, optical fibre technology is the clear choice.

HBM has completed its proven range of products and services for the measurement of mechanical quantities with first components from the field of photonic sensors. Electrical strain gauges and transducers are frequently used in addition to the optical sensors described in this paper. Therefore, HBM's hybrid solution which enables optical and electrical sensors to be connected at the same computer platform in a NTP-synchronized form, offers a significant benefit.

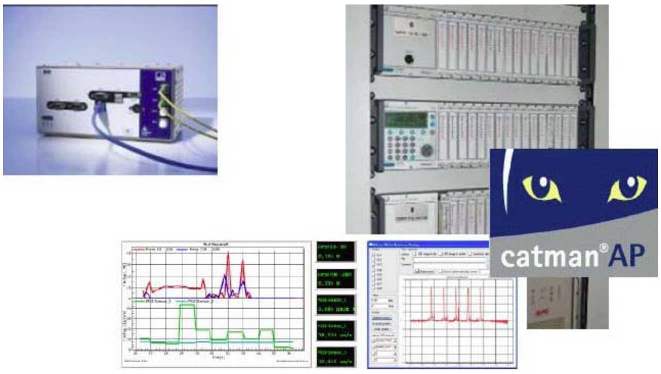

Figure 4. Hybrid system.
Slika 4. Hibridni sistem

Load monitoring is the first step in the calculation of the residual lifetime with respect to the structural health, under operational loads and in realistic conditions. Static as well as dynamic time responses of the signal have to be observed over long periods, sometimes for years.

Relevant loads for the fatigue of composite materials can be monitored best with optical strain sensors because of their high cyclic load behaviour and lower damage accumulation than metals.

Figure 5 shows HBM optical strain gauges, designed to guarantee a perfect strain transfer from specimen onto the optical fibre grating. This design of a patched optical Bragg grated strain gauge comes along with well known application procedures, skills and materials of electrical strain gauge applications, /11/.

HBM carefully selected a fibre type that meets the requirements of applications in structural testing and is well suited for fatigue observations and measurements of mechanical loads.

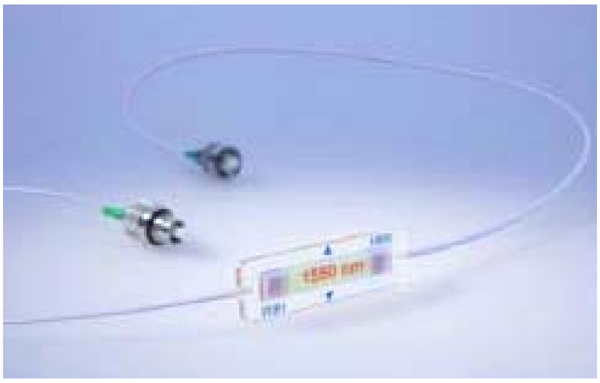

Figure 5. Optical strain gauge K-OP type, /12/.
Slika 5. Optička merna traka tipa K-OP, /12/

In addition to optical strain gauges with patch, HBM provides a system of glass fibre technology products, dedicated to project-based applications. That system is Optimet by HBM ™ which offers a gamut of features including patch cables, low attenuation fibre cords and bare or specially coated fibres for strain measurement and signal transmission.

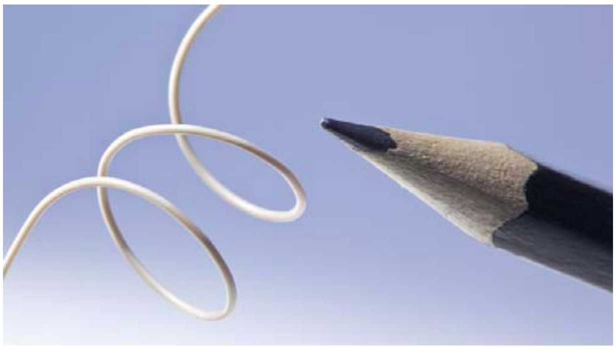

Figure 6. Fibre system OptiMet by HBM™ - PKF type fibre with incorporated Bragg gratings.
Slika 6. Sistem vlakana OptiMet od HBM™ - PKT tipa vlakna sa ugrađenom Bragovom rešetkom

The Bragg gratings are directly inscribed in the fibre during the fibre drawing process, followed by the coating process. Bragg fibres are highly robust and capable of measuring strains above 1%. Higher core doping permits bending radii of 2 mm, while commercial telecommunications fibres allow only 15 mm minimum bending radius. The result of smaller bending radii is outgoing light and strong attenuation of the optical signal.

Another outstanding advantage of these fibre gratings is their unequalled structural durability, resulting from homogeneous completion of the coating. HBM's optical strain sensors show an extremely low damage accumulation and excellent fatigue behaviour. So it is possible to use optical strain gauges of the K-OP series or OptiMet PKF coated fibre types in high-cycle fatigue tests, over 10 million load cycles, at strain levels of +/- 5 000 μm/m without collapse. This is a remarkable feature compared with electrical strain gauge applications using metal grids.

When considering the transition region of glasses due to elastic strain range in the S-N curve, the brittle fracture type should be noted. In slim optical fibres, no apparent plastic deformation takes place before fracture. In own tensile tests the maximum of the applicable pulling force was approximately 60 N, which is in very good agreement with the magnitude of the fracture strength of the coated fibre of 4 900 MPa.

Failures occurred in the experiments in optical fibre Bragg gratings by deviations of the peak shape, even after the applied strain of a few percent. However, these results are determined by the visco-elastic properties of carrier and adhesive. Through this study, several conclusions are reached. Depending on the used interrogation method, the error due to double peak splitting can account 1.5%, calculated as relative error. See here also Fig. 7.

In addition to the above uses, Bragg grating sensors offer potential in experiments for research and testing with regard to crack propagation or structural damage from repeated loading at high strain values, such as in the percentage range fibre optic strain gauges. However, the barrier for high-strain measurements often is represented by the performance of the adhesive. Figure 8 shows a clamp which allows to apply an embossed elongation of 3%. Here, the optical strain gauge is indeed blistered off, but still fully functional.

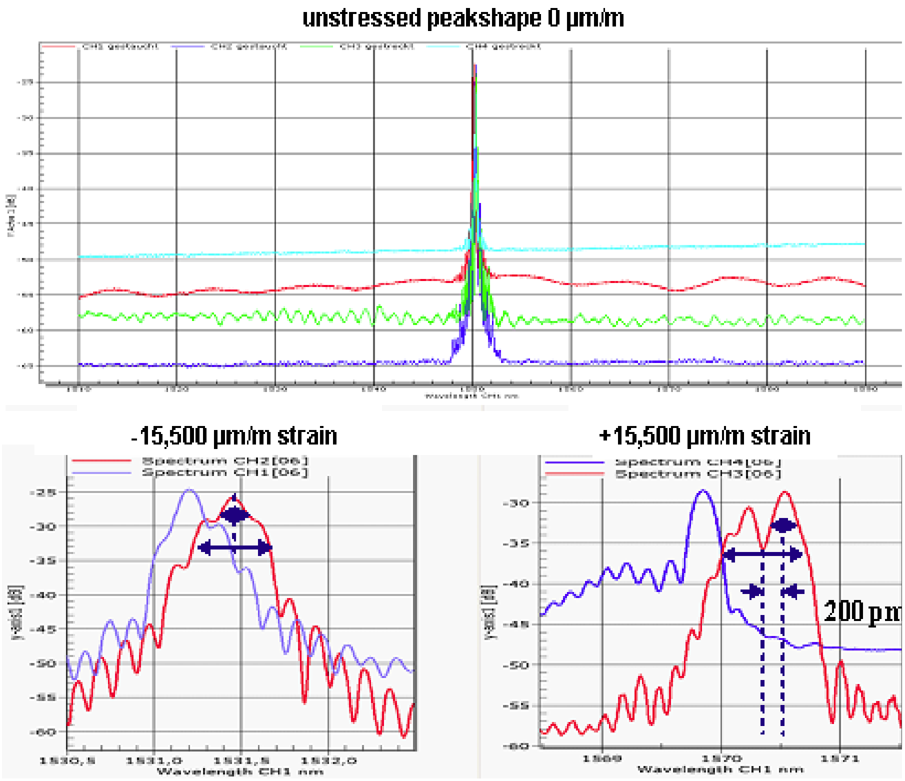

Figure 7. Peak shape distortion at +/– 15 000 μm/m strain load.
Slika 7. Distorzija skoka za +/– 15,000 μm/m deformaciju

In another experiment, a bare fibre type OptiMet OMF was set to a maximum strain of 3%. Surprisingly, even after several tensile tests, the unloaded stress state could be repeated without noticeable failure (Fig. 9). This is obviously related with the low degree of ductility of coated fibres.

Figure 8. Optical strain gauge at clamp, applied strain 3 000 μm/m.
Slika 8. Optička merna traka, deformacija 3 000 μm/m

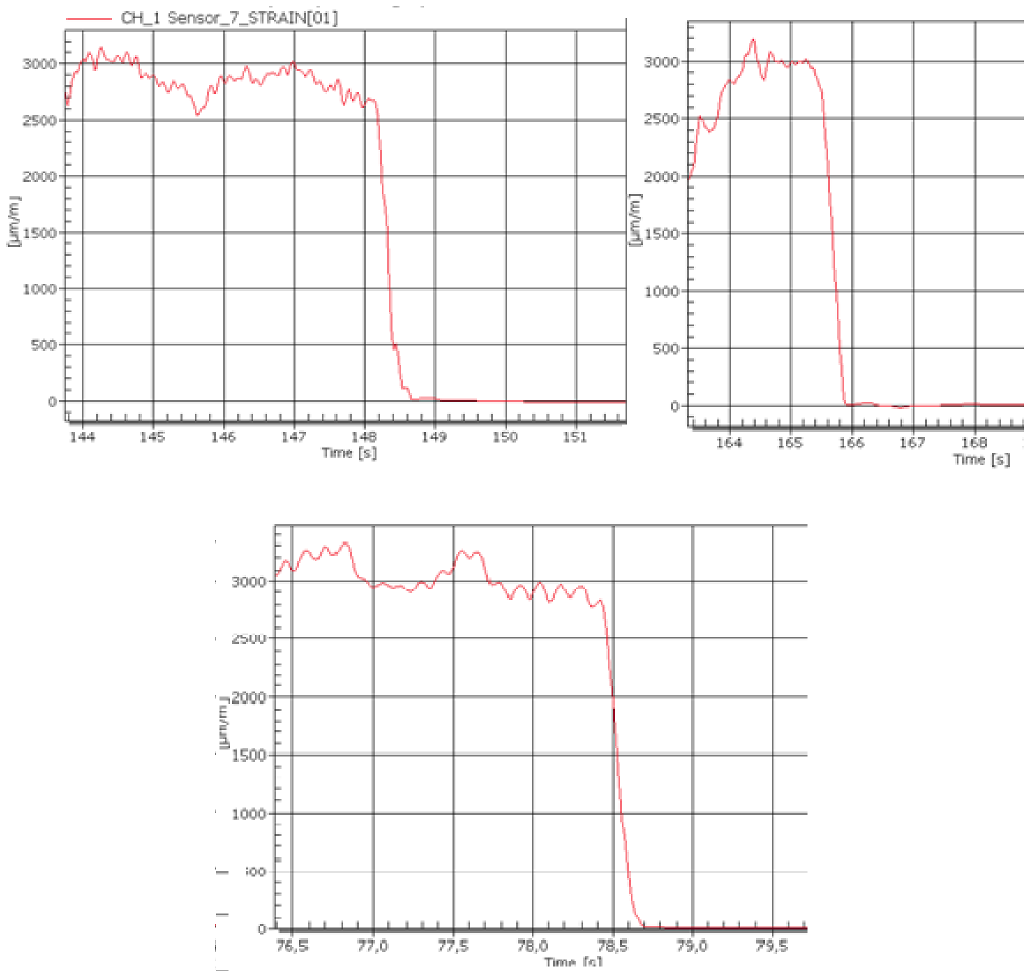

Figure 9. Bragg gratings reaction on 3% strain load (Type: OptiMet OMF).
Slika 9. Reakcije na Bragovoj rešetki za opterećenje sa 3% deformacije (tip: OptiMet OMF)

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