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Ringing Bells - State of the Art in the Durability Evaluation of Church Bells

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1 Damages on bells

Church bells are both musical instruments, strongly connected to the European culture as well as technical structures exposed to severe loading conditions during ringing. Many famous bells are in service for centuries and belong to the cultural heritage of the European Nations. On numerous bells damages occurred due to the continuous ringing. Destroyed ornaments and inscriptions on damaged bells lead to a severe loss of valuable cultural heritage. Possible repair measures require large efforts and cost. For example some years ago the famous German bell Gloriosa in the dome in Erfurt cracked. The crack was welded with extremely high cost and effort up in the tower, after having adapted the tower construction for the necessary works. In 2004 after investigations of the stresses and sound of the bell, it was found that the Gloriosa (Fig. 1) was cracked again and had to be repaired. This time the 12t bell was brought in an spectacular and with high cost down from the tower to be welded in a work shop and was brought back in 2005.

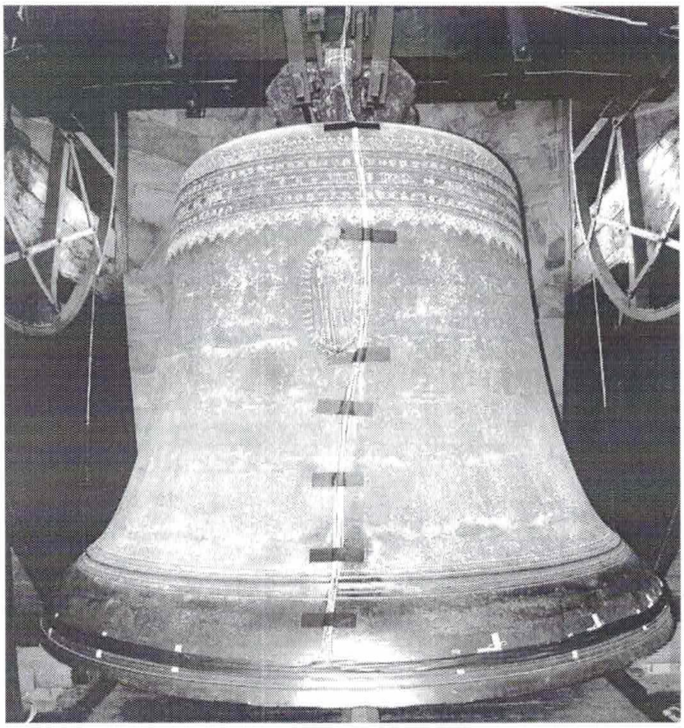


Fig. 1: Gloriosa with strain gages, Erfurt, casted in 1497,

Especially damage and wear is observed on bells, which were equipped with clappers from new steels 50 to 80 years ago. The new wear is decisively larger, than the wear observed before over centuries. It therefore must be expected, that in the next years multiple and severe damages occur on a large number of historical important bells. Often replica of the original bells were re-casted with the respective high cost for the concerned parish or the bell caster, e.g. in Hall Tirol, Austria a bell was cast 6 times for repeated damages after always about 4 to 7 years. Discussions about the responsibility of damaged bells are extremely difficult. Damages on newly cast bells are often referred to the responsibility of the bell caster for more or less good reasons.

Also the clappers striking the bells are exposed to severe stress conditions and fracture may lead to dangerous fall down of the heavy steel pieces, e.g. summer 2003 in the dome in Speyer Germany or New year 2005/06 in the cathedrale of Donauwörth.

2 Engineering view on ringing bells

Damages on bells occur due to various reasons, such as:

- material wear
- fatigue loading
- material insufficiencies,
- the clapper dimensioning, its weight, material and shape,
- belfry characteristics e.g. cross beam type, fixation, as-symmetry,
- severe ringing conditions e.g. high angularity.

The system bell-clapper-belfry system being in service under ringing conditions different from region to region has been developed over the centuries, mainly based on intuition as well as tradition. The technological mechanisms and reasons for the damages and fractures are widely unknown. The influence of the main parameters has not been understood.

It is of great importance to note, that the way to ring the bells is different in the European countries for example, the angularities in Germany are with about 50° rather small compared to Austria with 120° or to Italy with nearly 180° or Spain where the bells are turned around completely. In England the tradition of change ringing, where many people ring the bells according a harmony for many hours is well known.

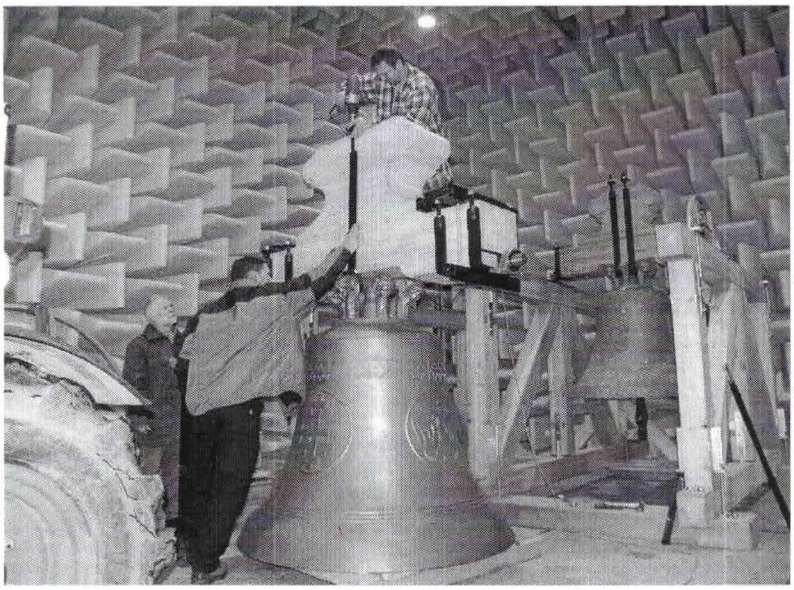


Fig. 2: Bells being set up for ringing tests in the laboratory

In the last years several projects on the life of bells were performed, However, due to the manifold technical problems and the high number of parameters, none of the small enterprises was able to determine adequate results from small individual investigations. A joint project therefore was started with 8 bell foundries, clapper manufacturer, the church, the TÜV and 3 Universities. The aim of the project is, to investigate the damage mechanisms on bells, to determine the main influencing parameters e.g. clapper, ringing conditions, dynamic set up, and to elaborate field procedures and respective data for a smooth ringing of bells with a high musical quality.

3 Material investigations of bell bronze

A ringing bell is a fatigue loaded structure, the evaluation of its life can be performed with the same methods used to evaluate the fatigue life of other structures e.g. automotive components. In a research project funded by the the German Association of Industrial Research AIBF carried out at the Fraunhofer Institute LBF in Darmstadt [1] extensive fatigue tests were performed on specimens cut from a broken bell. Bell bronze is an alloy, which consists of about 80% copper (Cu) and 20% tin (Sn) since the 15th century. The alloy is difficult to harmonise. A content of tin over 13% results in a reduced strength and ductility, but increases the hardness. The bells of the middle ages vary widely in their content of tin [10]. Since the strength properties of an alloy do not cannot simply by derived from its content, investigations on bronze specimens from a todays standard bronze may therefore not directly be transferred to old bells. The presented results of fatigue tests are valid only for the alloy under investigation with its specific cooling down history.

3.1 Mechanical and metallurgical properties

The specific weight of the bell bronze is about $\rho = 8.4$ kg/dm³. The Youngs Modulus and the tensile strength were determined from tensile tests on the specimens cut from a bell as $E = 98600 \pm 720$ MPa and $R_m = 126 \pm 18$ MPa. The specific weight and the Youngs Modulus correspond well whereas the tensile strength is decisively lower than given in the literature. The high scatter and the low strength may result from the specific cooling down history after the casting of the bell and its specific porosity [1].

The Brinell hardness of the bronze was measured as 179 ± 18 HB corresponding well to information provided in the literature. Low load Vickers hardness measurements show the different parts of the micro structure of the bronze. For the primary phase α a Vickers-hardness of 107 ± 3.6 HV0,3; the interdendritic α+δ-Eutektoid had an average hardness of 321 ± 46 HV0,3. The δ-phase is mainly responsible fort he hardness of the bronze.
By a chemical analysis of the material under investigation the following contents were determined: 78.4 % Cu, 20.6% Sn, 0.11% Ni und 0.22% Pb. The content of the alloy did not vary through the thickness of the bell of roughly 15 cm in the sound burp. In the bronze pores with an average diameter of about 0,2 mm and extrema of 0,5 to 1 mm were observed, which result from the casting process with about 4% nitrogen(Si).

3.2 Wear

The highly dynamic impact of the steel clapper on the bronze bell leads to elasto-plastic deformations and micro structural changes on the surfaces of both components., which lead to wear (DIN 50320). The surface wear leads to crack initiation and propagation. Additionally material particles may be disrupted and adhesion occurs due to atomic connections of the two contacting components (micro welding) and their brake up. The disjunction often does not occure in the initial contact plane but inside the bell; bronze will be attached to the clapper surface. The roughness of the surfaces may also be increased, and besides the material transfer small holes may occur [1 to 3 and 8].

No systematic investigations on the main parameters determining the wear of a bell are known. Planned investigations therefore concentrate on the clapper shape, material, hardness and its guiding, being responsible for the size of the possible contact area.

3.3 Fatigue strength

The clapper hits the bell continuously in 2 locations, where the bell is deformed respectively. The subsequent ringing with the frequency of the tones of the bell is a result of the material deformation amplitudes with those frequencies. Thus the bell is a fatigue loaded structure which is loaded under ringing conditions under a specific ringing spectrum dependent on the severity of the clapper impact and the resulting deformations as well as on the damping of the bell leading to decreasing stress amplitudes. The fatigue strength of the material determines how long the bell can be exposed to the occurring stress conditions. Fatigue tests were performed under tensile and bending loading on specimens cut from a bell. Besides the high scatter of the fatigue strength of the specimen, the obtained fatigue strength is rather low, compared to data from the literature from tests on specially cast material specimens.

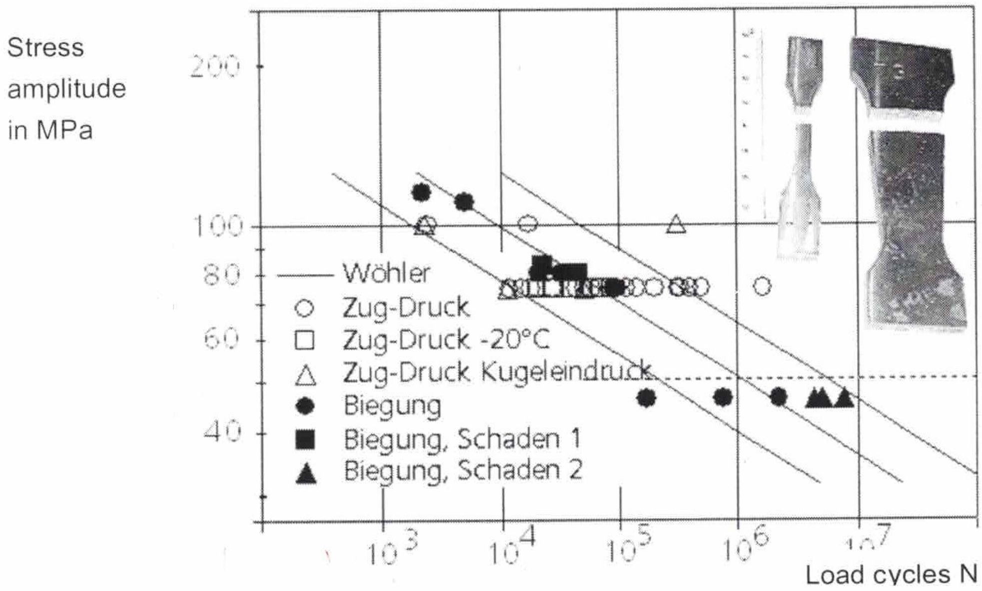


Fig. 3: Results of fatigue tests on specimens cut from a bell [1]

From the test results a Woehler curve was determined for a stress ratio R=-1 and a probability of survival of 50% with a slope of k=6 and the fatigue strength at a cycle number of $N=10^6$ to σ_a=50 MPa with a scatter of $T_{N\,(10\%,\,90\%)}$ = 1 : 25. No significant difference of the fatigue strength was found on specimens cut from the inside, the middle or the outer surface of bell. Tensile and bending loading resulted in the same fatigue strength. No influence was found due to temperature in the range of -20°C to 20°C.

To investigate the influence of wear on the fatigue strength of the bell material, a pre-damage was introduced to a selected number of specimens. Once a steel ball with a diameter of 10mm was pressed on the specimen surface leading to an indentation of about 1.5 mm diameter and 0.12 mm. Other specimens were pre loaded by a repeated hammer test with varying hammer weight until an indentation similar to that of the static tests was observed [4].
The influence of hammer material and hammer shape on the accumulating wear and material disruption was not investigated yet, but may be of major importance to understand the damages of bells. The hardness of a steel hammer for such investigation should be similar to the hardness of actual clappers. The new clappers used for the measurements (chapter 3) with a ball and an ellipsoid shape showed an initial hardness in the range 115 HB and 135 HB thus being lower than then the hardness of the bronze with about 179 HB.

4 Measurements on bells

4.1 Residual stresses

Residual stresses were measured on a 800kg bell [1] with the bore hole drilling method in and outside at the sound burp. Tensile residual stresses were identified on the inner side which however occurred only on the surface and decreased rapidly into the material. These residual tensile stresses may be explained with the cooing down process. The outer side of the bell is expected to cool down before the inner side; on the inner side then tensile stresses will occur due to restricted shrinking by the already shrunken outer material. The observed tensile stresses are considered a positive for the strength of the bell, since the clapper induces compression in the area of the impact, compensating partly the residual tensile stresses.
The measurements were performed only on one bell. The residual stresses identified with the bore hole method, showed a high scatter. The mentioned residual stress conditions therefore may be handled as an single result, which must be proved by further investigations on other bells and probably with other measuring technologies.

4.2 Stress analysis, acceleration and sound measurements

Bells are hit by the clapper during ringing repeatedly. Each clapper stroke results in a local deformation of the bell and subsequent stress cycles with the different superimposed frequencies of the bell. Besides the harmony of its tones the quality of a bell is determined by the damping of the individual tones, the decrease of the stress amplitudes after the stroke.

Stress measurements were performed with strain gages on a number of bells in the laboratories and in the towers, to measure the local stresses during ringing under different conditions. Strain gages were applied on the sound burp in circumferential direction, the direction of the first principle stress, mainly in the cross section of the contact areas inside and outside, as well as around the circumference of the sound burp (Fig. 4a).

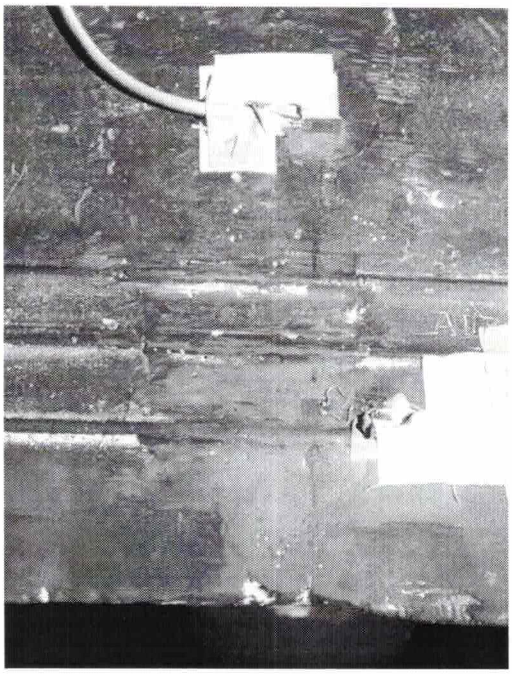


Fig. 4a Strain gages on a bell

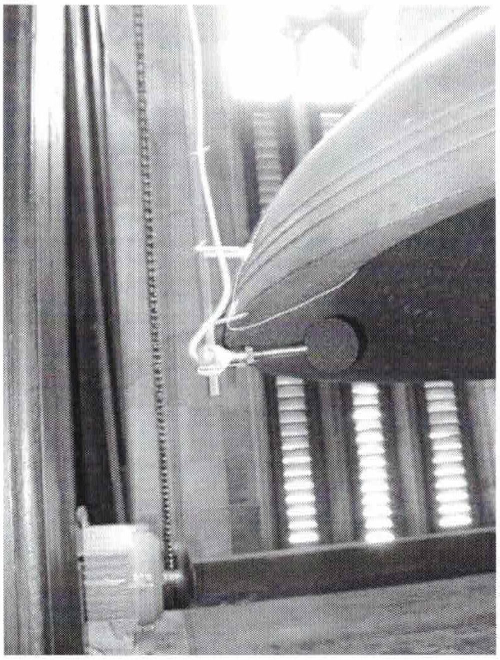


Fig. 4b Microphone for objective sound

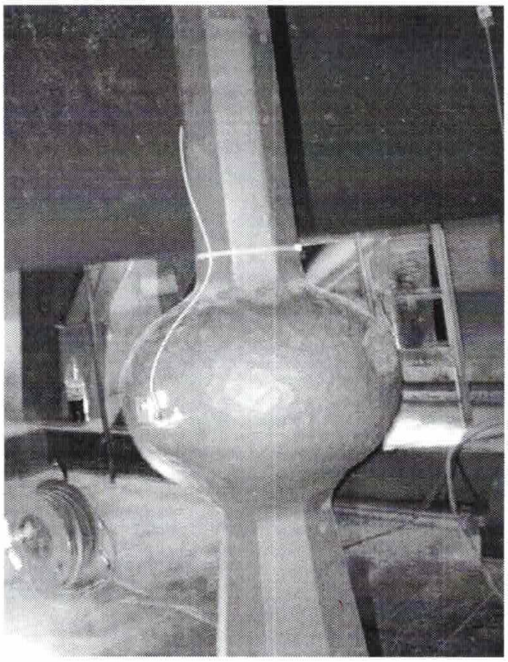
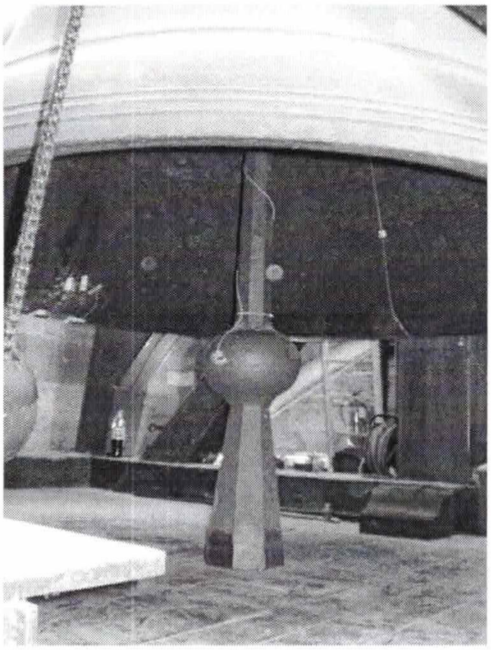


Fig. 4c: Accelerometer on a clapper



5 Analysis of strain, acceleration and sound measurements

The most important parameter, which determines the loading of the bell is the clapper impact, which is described by the clapper acceleration during the stroke. A bell in service is repeatedly hit by the clapper. The intensity of the clapper impact is determined by the set of parameters of the dynamic system but at the same time is a parameter varying statistically. Accelerometers were bonded to the clappers, to identify the intensity of the individual clapper strokes (Fig. 4c). The bells however are musical instruments, which are loaded the mother, the less loud they are ringing. Therefore also the sound pressure of the bell is recorded during the measurements, to be analysed in view of the characteristic sound (Fig. 4b). The characteristic sound of the bell depends on the type, shape and material of the clapper and the intensity of the clapper impact. Fig. 5 shows the strain and the clapper-acceleration time histories just before and after the clapper stroke during 20 msec at one side (0° pos. acceleration) and the other side (180°, neg. acceleration) on strain gages outside on the sound burp opposite to the clapper impact area. Tensile strains occur directly opposite to the clapper impact area and after a certain time, which the shock wave needs to run around the bell a tensile strain can be observed on the other side. The clapper impact lies in the range of 500g, which occurs during about 0.5msec.

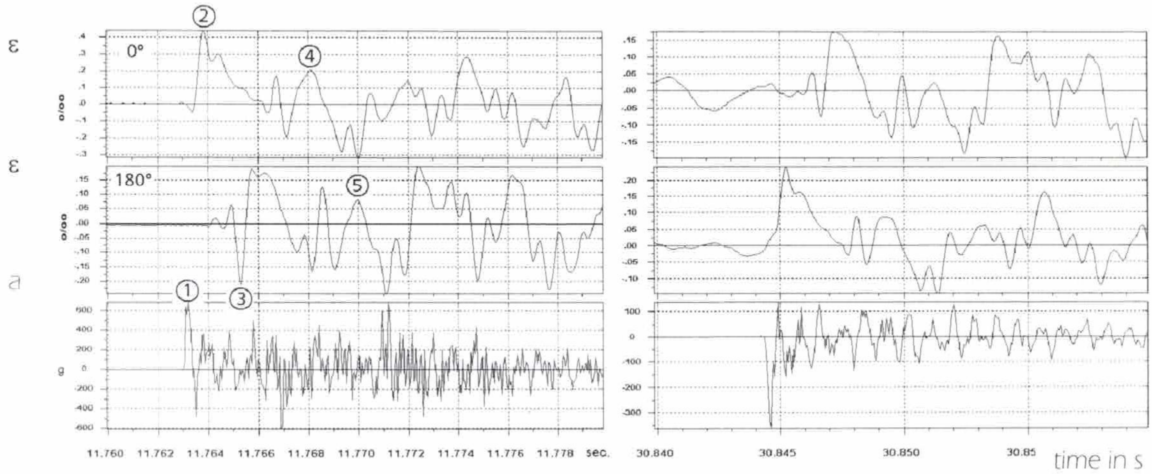


Fig. 5. Time histories of strains on bell and clapper acceleration

The stresses on the bell and impact intensities under the varied parameters of investigation however are subjected to statistical analysis, since each stroke is different from the others even for the same ringing parameters, see the clapper accelerations during 150s ringing in Fig. 6.

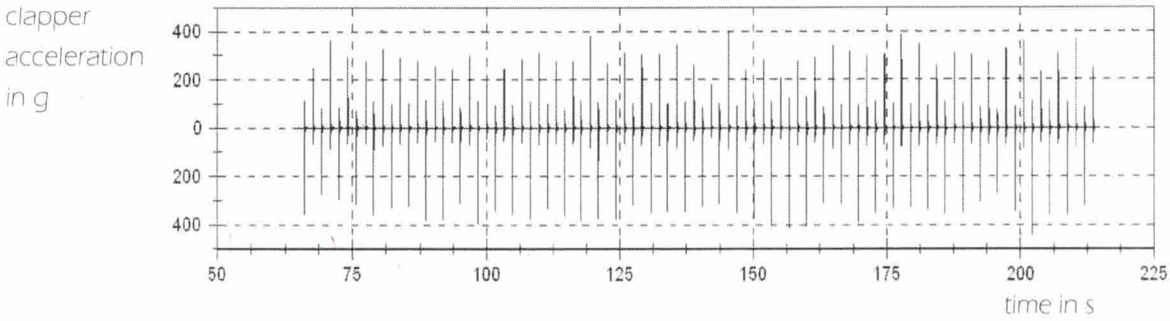


Fig 6: Acceleration during 150s ringing

A reference ringing of 1min was defined, to compare the influence of the individual parameters on the strain and clapper accelerations statistically. Measurements were performed on different bell clapper systems under possible parameter variations:

- clapper type – ball or ellipsoid
- clapper balance – extra weight was attached to the lower clapper
- ringing angularity of the bell from about ±35° to ±70°

Further important parameters were varied in the investigations as yet:

- Clapper material
- Clapper guidance
- Clapper contact geometry
- other clapper types e.g.

Then the influence on the fatigue life was calculated based on the rainflow counting (Fig. 7) of the strain time history during the reference ringing of 1min and a damage accumulation calculation was carried out referring the strain amplitude spectra to the Woehler curve (Fig. 3) gained from fatigue testing on specimen cut from a bell, Fig. 8.

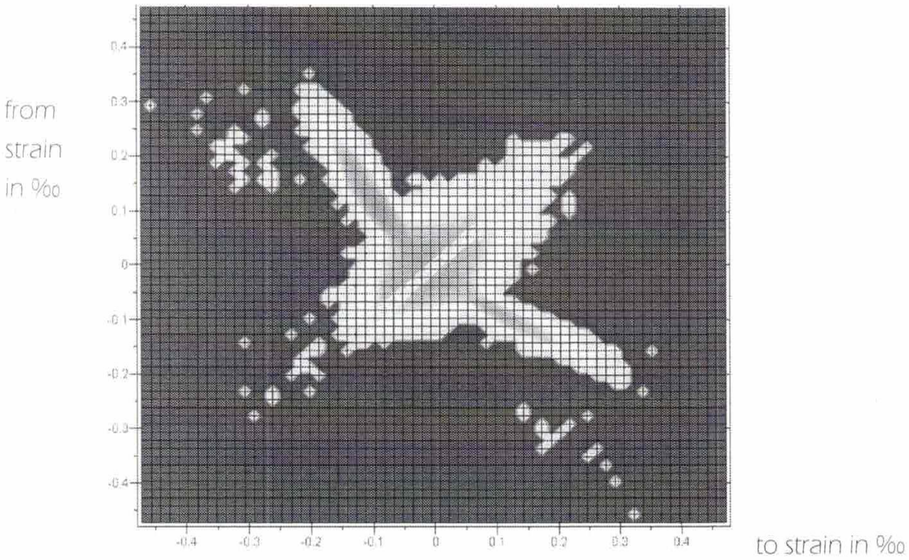


Fig. 7: Rainflow matrix of strain outside sound burp opposite to clapper impact, 1min

As a result of these investigations in [1,2,3] the following conclusions can be drawn.

- Bells are fatigue loaded structures.
- Strain gages are capable to measure the fatigue relevant stress conditions on bells, even on the patina when taking special care and using adequate adhesives.
- By experimental stress analysis during a 1min-reference ringing, the influence of varied parameters on the stress conditions, the loading and the life of a bell could be determined.
  - the influence of the clapper shape (ball or ellipsoid) did not result in significantly different stress conditions.
  - changes of the ballast of the 80kg-clapper by 4kg extra weight showed no influence on the stresses.
  - The stress conditions on the two sides of the bells under investigations was decisively

different (see Figs. 6 and 10), but could be equalised by adjustment of the bell in the yoke.

- An increase of the ringing angularity up to ±90° resulted in a significant increase of stresses and thus a reduction of expected fatigue life, by calculation of 14% per degree of higher ringing angularity – Fig. 8.

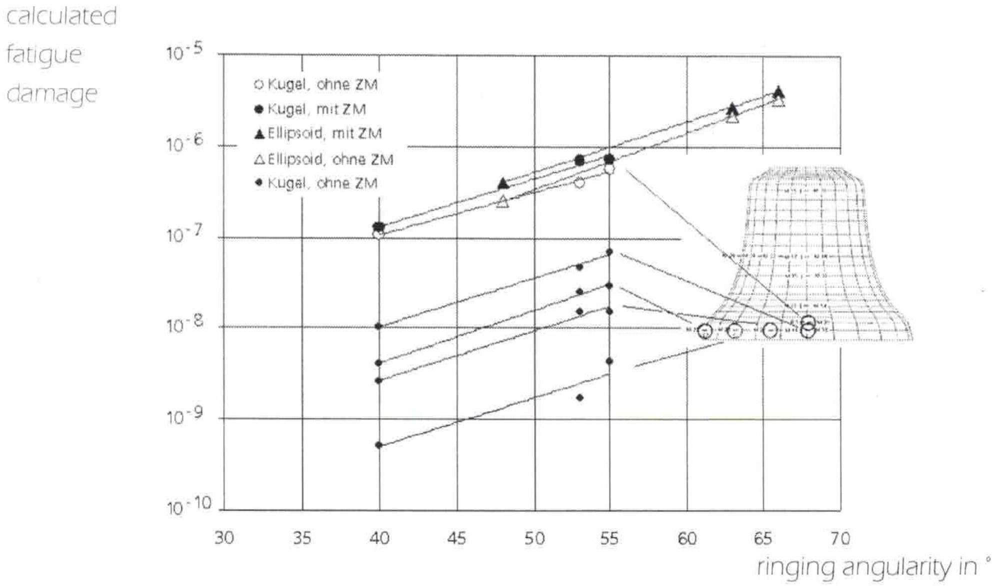


Fig. 8: Influence of selected parameters on the calculated fatigue damage(1min ringing) under varied parameters in different cross sections of a bell [1]

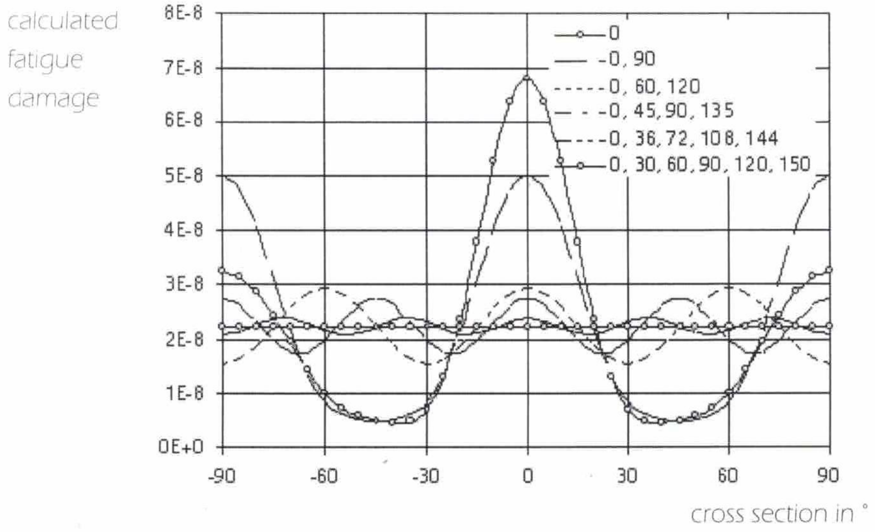


Fig. 9: Calculated damage (1min ringing) over the circumference of the bell and its reduction due to possible turning of the bell [1]

These analyses show that the accumulating fatigue damage of bell is highest in the cross section of the 2 clapper impact areas and nearly the same under 90°. A minimum of calculated damage was obtained under angularities on the sound burp of 30 to 60° - Fig. 9, curve 0. It can be concluded that turning the bell by 30° from time to time, leads to a changed impact area of the clapper and a reduced accumulated damage on the circumference. This measure may increase the total life of a bell by at least a factor of three.

These analysis only take into account the fatigue damage due to the stress amplitudes but not the influence of wear. However in the fatigue tests an influence of wear on the fatigue life was not identified under the chosen conditions.

The sound pressure is analysed in a referenced way to evaluate the composition of the sound in view of the individual tones, their energy in the spectra and the damping of the individual tones. The sound pressure may be referenced to the impact energy derived from the clapper acceleration – Fig. 10.

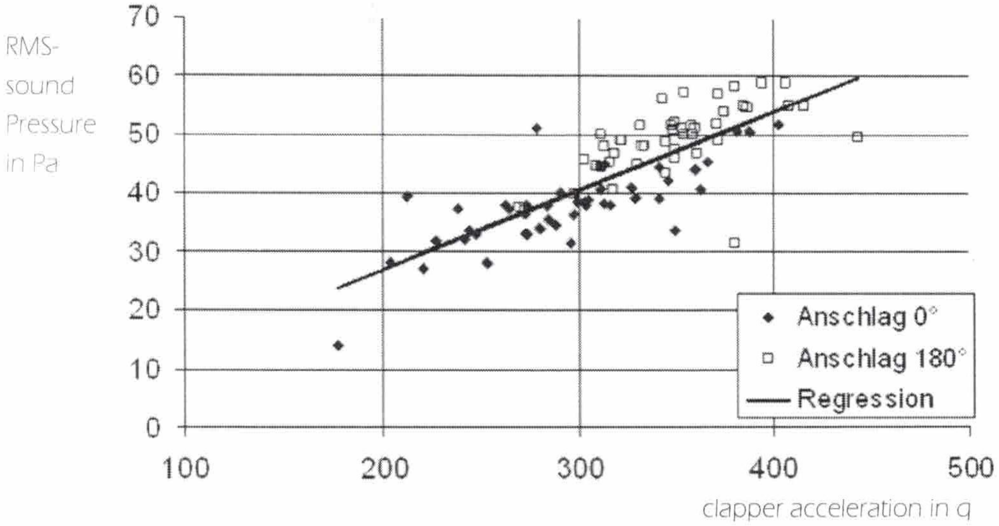


Fig. 10: Correlation of sound pressure and clapper acceleration

Bells are loaded least severe, if they are not rang at all. However, the bells are musical instruments and should ringing with an adequate loudness and with a high quality sound. Therefore, with microphones the sound was measured and analysed. In Fig. 11 the power spectral density is shown as an example, from which the individual tones of a bell and their intensity can be derived. However, a methodology how the sound can be measured and analysed for repeated measurements, especially the intensity of the different tones and their damping is most difficult since each stroke is different. Moreover, the sound emission in each cross section of a bell may be different due to small un-unimformities in thickness and shape. For sound measurements the environment plays an important role, the bell room in the tower. Also the location of the microphones whether located stationary in the bell room with a swinging bell or on the bell, in- or outside in selected cross sections will lead to quite different results in the physically measured sound. Standardised methods need to be worked out for a robust measurement, evaluation and presentation of the sound of a bell.

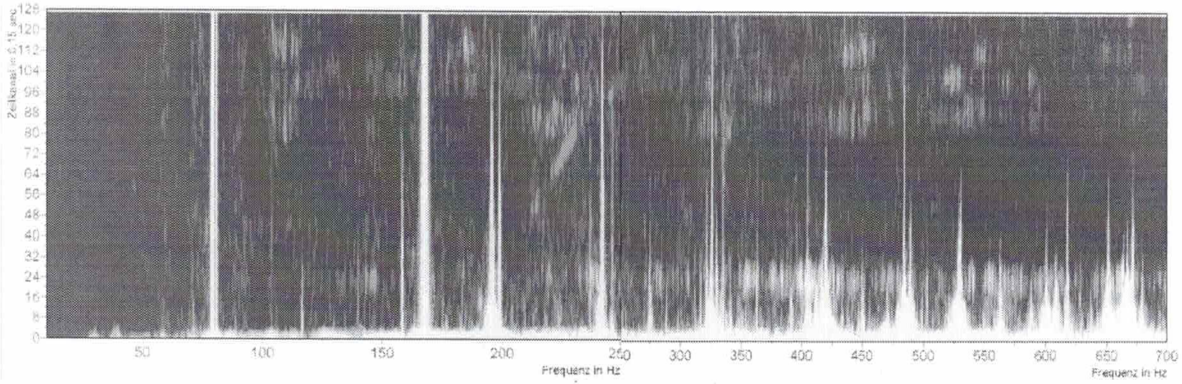


Fig. 11: Waterfall diagram, power spectral density of the sound pressure over about 20 sec after clapper stroke

6 Computer simulation

The measured stress, acceleration and sound data are used, besides their direct analysis as input data and for the verification of computer models. In computer models parameters can easily be changed for the investigation of their influence. Each calculation can be performed under exactly repeatable conditions. However, these models must be adequately verified. Finite element calculations can be used to calculate the stress conditions. In the following example the influence of a reduced thickness of the sound burp due to wear was studied. The model first was verified by a modal analysis which had to reproduce the sound of the bell with a reasonable accuracy, Fig. 12.

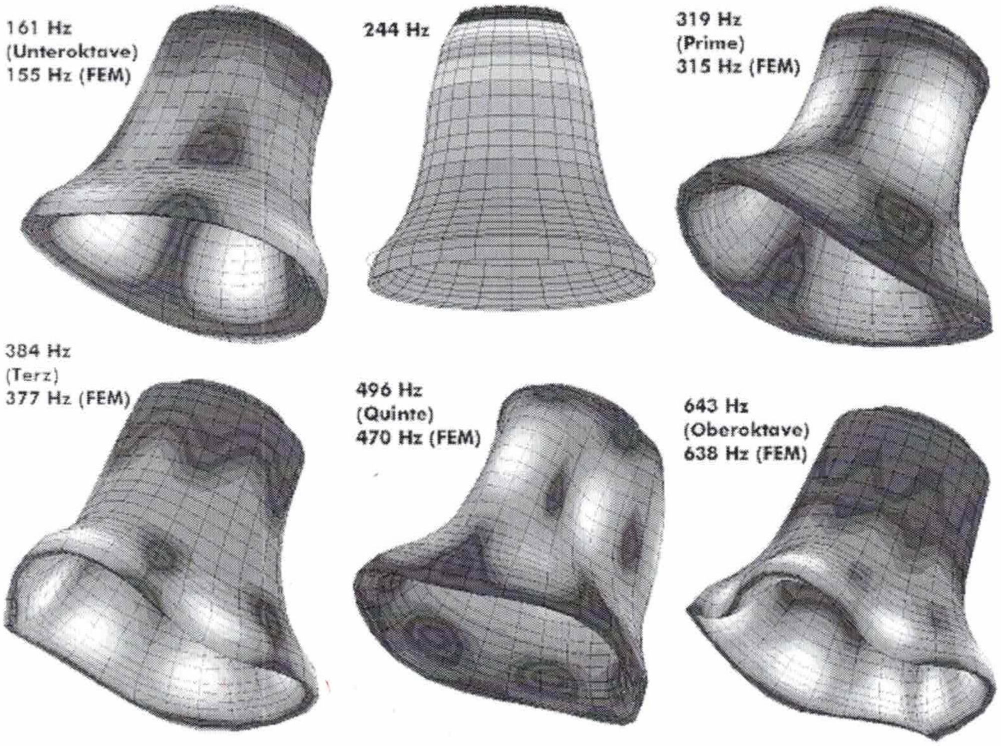


Fig. 12: Modal analysis of a bell for verification of the model [1]

The verified model was subsequently used to calculate the stress time history at the outer sound burp during a clapper stroke with a maximum acceleration of 500g applied sinusoidal during 0.5msec. The experimentally measured and the computed stress time history were in a good coherency. In the model then the sound burp was reduced at the clapper impact area be 10% in thickness in a shape similar to observed wear.

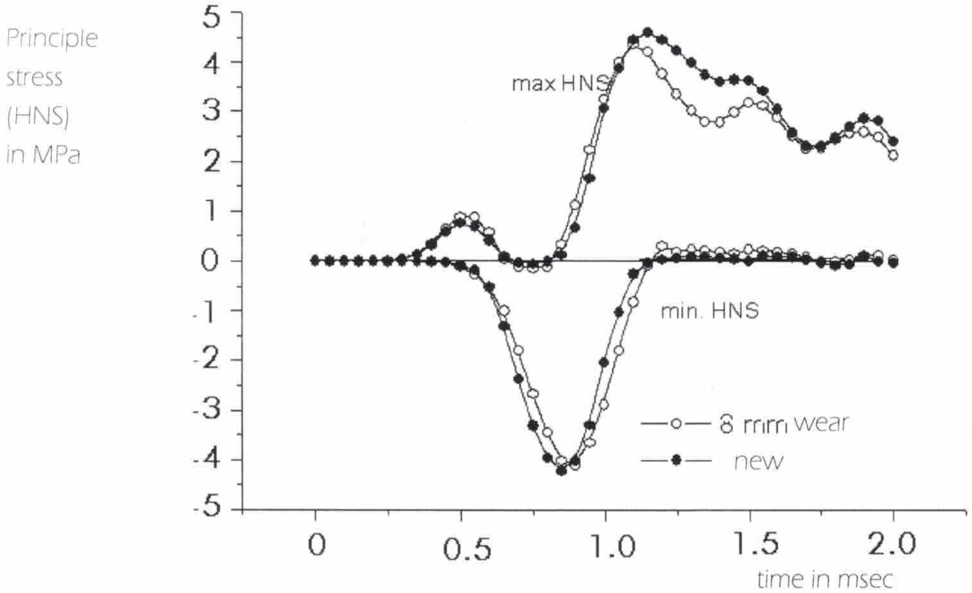


Fig. 13: Principle stresses at the sound burp during clapper impact on a new and bell with wear

Fig. 13 presents the time histories of the principle stresses at the sound burp in the "new" and the 10%-wear condition. The results of the fatigue tests indicated no significant decrease of fatigue strength of the material to local high cycle impact loading. The calculation of the stress conditions do not show a significant increase of local stresses due to a reduction of thickness by a 10% wear. Therefore no reduced fatigue life would be expected on a bell, due to wear up to 10%. However, further investigations should concentrate on the influence of the wear on the material strength.

6 Conclusions

Bells are both, musical instruments and structures exposed during ringing service to severe loading. Damages on bells occur due to fatigue loads and wear by the clapper impact. Engineering methodologies and tools e.g. experimental stress analysis and measurements of dynamic quantities are useful in combination with sound measurements and evaluations for evaluation of ringing conditions in view of smooth loading but high musical quality.

The elaborated methods and data allow to evaluate the fatigue life of bells based on measured stresses on the sound burp. The turning of a bell from time to time, so that the clapper will hit in a cross section of about 30° from the previous one, will lead to a conserving and safe ringing during a longer life.

An increase of ringing angularity will lead to a harder clapper impact. A harder clapper impact results in higher stresses and thus in a reduced life of the bell.

Fatigue tests on new and pre-damaged specimens which were cut from a bell did not show significant differences in fatigue life. A 10% thickness reduction due to wear does not lead to an increase of stresses compared to a new bell. These results indicate, that wear of up to 10% does not lead to a risk for damage on the bell.

The clapper impact and the sound level are correlated. All bells under investigation showed a clear unbalance of clapper impacts on the one and the other side, leading to high fatigue loading on one side. Arrangement of the bell in the yoke leads to a balanced clapper impact and a respective reduction of fatigue loading on the one side.

The influence of parameter on the fatigue damage and the wear of bells are under investigation in the European Research Project PROBELL since 1. Oct. 2005 (www.probell.net)

7 Acknowledgment

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