Holographic interferometry on the elastic deformation of prosthodontic appliances as simulated by bar elements

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Wedendal, P. R. & Bjelkhagen, H. I. Holographic interferometry on the elastic deformation of prosthodontic appliances as stimulated by bar elements. *Acta Odont. Scand.* 32, 189—199, 1974.

Prosthodontic appliances, especially two types of fixed bridge-work, were simulated by means of 7 series of bar elements, cast in a gold alloy. Elastic deformation studies were made in a bench installation. Double exposure holographic interferometry was performed using a continuous helium-neon laser in which forces applied to the bar elements were increased between exposures. The effect of force increases up to 1.5 N could be determined by analyzing the resulting interference fringe patterns. In all, 170 double exposed holograms were evaluated and photographically documented. Differences in the deflection characteristics of the bars were studied with the aid of two composite histograms. Variations in the elastic deformation could be traced to technical reasons, such as the casting technique and the presence of soldered and screw-locked joints. The stiffening effect of internal ivory cylinders simulating teeth prepared as full-crown abutments was proved. The sensitivity of the method as well as the measuring range depend on the wave-length of helium-neon laser light (0.6328 μm).

Key-words: Holography; interferometry; lasers; prosthodontics

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Clinical investigations of the momentary deformations within fixed bridge-work caused by low-level masticatory forces are difficult to perform, because very high measuring sensitivity and rapid recording techniques are mandatory. Laser metrology provides a new technique for this form of dental research. Since its introduction 10 years ago methods have been developed to make high precision measurements via holographic interferometry. The sensitivity and measuring range of these techniques depend on the wave-length of the laser light used. Investigations concerning dental materials have been performed previously (*Wedendal et al.*, 1972; *Wictorin, Bjelkhagen & Abramson*, 1972).

The purpose of the present investigation was to study the elastic deformation of prosthodontic appliances during simulation experiments. These studies were a preparation for further clinical investigations.

Received for publication, April 18, 1974.

MATERIAL AND METHODS

The test specimens were designed in the shape of bars with the intention of simulating prosthodontic appliances, and fixed bridge-work in particular. The dimensions were chosen according to the average dimensions of gold bridges for clinical applications. Soldered joints, screw-locked joints and hollow cylinders simulated various aspects of clinical bridge-work.

Six series of gold bars were manufactured. Delrin acetal resin* was used to make models for the bars prior to embedding in Cristobalite. The dimensions of each Delrin model were 80.00 × 6.50 × 4.00 ± 0.05 mm. Two different methods were used for embedding and casting.

Method I. The Drelin model was sprued parallel to a wax rod of equal size before embedding, according to conventional crown- and inlay technique. (*Hedegård & Wennström*, 1960).

Method II. The Delrin model was embedded in Cristobalite with one end open for casting.

Casting was made in C-gold, Sjöding. Gold alloy solder 820 Sjöding was used in soldered joints (*Sjöding*, 1970). A screw-lock (*Wedendal*, 1973) (Fig. 1) was used in the D-bars, the male and female parts being separately waxed on to the two Delrin bar elements before embedding. The screw-locks were enclosed in the gold and the rigidity of the screw-lock system was further optimized by supplementary contact surfaces (Fig. 2). The characteristics of the test specimens are summarized in Table I.

By means of laser metrology (*Wedendal et al.*, 1974) the average angle of tolerance within the screw-lock system was determined to be 0.42° with the locking screw tightened and 0.78° without the locking screw.

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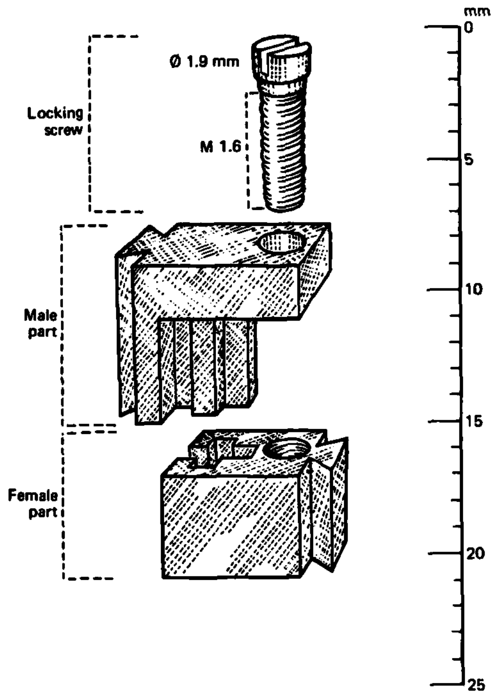

Fig. 1. Screw-lock.

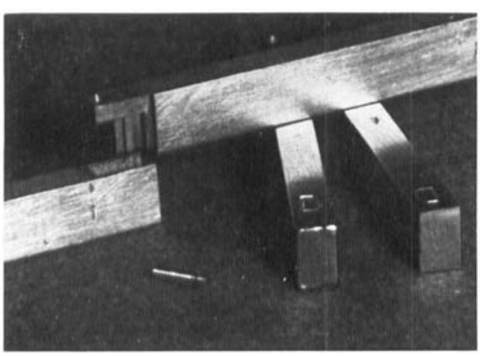

Fig. 2. Close-up view of screw-locked bar elements.

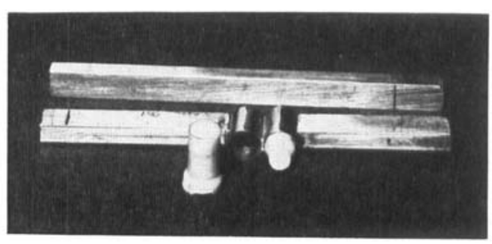

Fig. 3. View of solid bar and bar elements enclosing ivory cylinders.

Table I. *Survey of test specimens*

Code	Number	Description	Casting method
A	4	1 bar element	I
B	4	1 bar element	II
C	4	2 bar elements separate casting 1 soldered joint	II
D	4	2 bar elements separate casting 1 screw-lock	II
E	4	8 bar elements separate casting 7 soldered joints	I
F	4	2 bar elements separate casting 2 hollow cylinders, closed in one end, waxed up as »full crowns» on ivory cylinders ∅ 10 mm; thickness 0.5 mm; 3 soldered joints (Fig. 3)	II
As	4	The A-bars, cut in two equal parts. 1 soldered joint	I

Radiographic control. The bars were tested radiographically (*Henriksson, Wictorin & Österberg*, 1973). Evaluation was made as regards the position of defects and areas of reduced density, the findings being indicated in schematic drawings.

Holographic interferometry

A helium-neon laser (Spectra Physics 125)* was used in the present investigation. Registration of the holograms was performed in a vibration-free laboratory installation (vibration amplitude required to be $<\frac{\lambda}{8}$).

As shown in Fig. 4 the expanded laser beam illuminates the object and the reference mirror during the exposure. The interfering wave-fronts of the reflected object beam and reference beam create a unique primary interference pattern within the emulsion of the holographic plate. In the holographic interferometry technique utilized in this investigation two exposures were made. The second exposure was made after the force applied to the object had been increased.

The interference between the object beam, reflected from the bar before and after deflection and the reference beam create a displacement secondary interference pattern in the holographic plate. The wave-fronts of the laser light alternately intensify and extinguish each other

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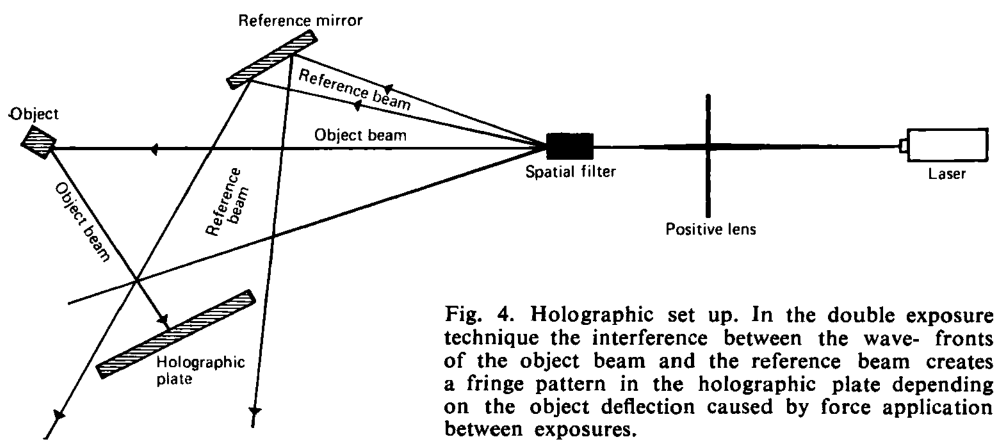

Fig. 4. Holographic set up. In the double exposure technique the interference between the wave- fronts of the object beam and the reference beam creates a fringe pattern in the holographic plate depending on the object deflection caused by force application between exposures.

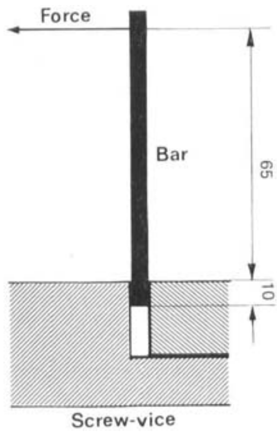

Fig. 5. Test object in one end screw-vice fixation.

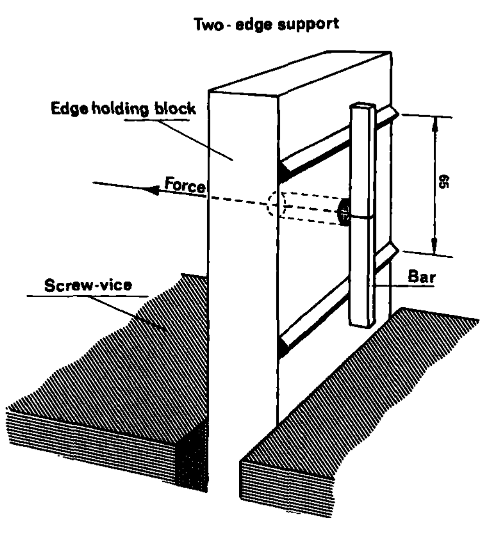

Fig. 6. Test object on two-edge support.

resulting in bright and dark fringes. The spatial resolution of the fringe pattern then depends on the wave-length of the laser light.

Reconstruction of a hologram. After registration, developing and fixing the exposed holographic plates were illuminated by means of a laser beam, aimed in the same direction as the reference beam. A virtual image is observed when looking through the holographic plate. The number of interference fringes appearing on the three dimensional image were then counted. The virtual image of each hologram was photographed in a special photographic set up.

Fixation of The Test Specimens. During the experiments two different methods were utilized for fixation of the test specimens, according to standard techniques for mechanical strength investigations.

I. The one end screw-vice fixation is shown in Fig. 5. This way of fixation simulated free end parts of extensive bridge-work, the screw-vice being analogous to the parodontally fixed part of the bridge. Deflecting forces were applied to the bar 65 mm from the screw-vice.

II. The two-edge support is shown in Fig. 6. In this arrangement the bar simulated pontics within a suspension bridge. The two edges were analogous to proximal abutments. Forces were applied to the bar at a point equidistant from the edges.

Error estimation

Error is caused by practical difficulties in resolving the center of the last interference fringe. The evaluated displacement of the point of force application has a maximum error (Δ d) such that $\Delta \mathrm{d} = \pm (0.1\ \mathrm{d} + 0.3\ \mu\mathrm{m})$, where d = total displacement of bar surface.

Technical data

Laser: Spectra Physics model 125

Wavelength	632.8 nm
Output power	60 mW
Transverse mode	TEM_{00}
Beam diameter	2.0 mm
Beam divergence	0.7 mrad
Polarization	1: 1000
Resonator length	1800 mm

Spatial filter: Spectra Physics model 332

Holographic material:

Agfa Gevaert Scientia	8 E 70
Sensitivity	200 erg/cm²
Resolving power	3200 lines/mm
Support: Glass plates	1.2—1.4 mm
Size	9×12 cm
Thickness of emulsion	7 μm
Developer	G 150
Fixer	G 334

RESULTS

Preliminary experiments

The holographic set up was arranged for convenient later analysis with the holodiagram (*Abramson*, 1969). The k-value was calculated as 1.2.

Tests were performed in order to ensure adequate screw-vice fixation. The magnitude of friction within the force application arrangement was calculated according to the moment equation of *Boestad* (1969). The range of force application was chosen for experimental convenience.

Nature and amplitude of applied forces. Forces were applied to the bars in a direction parallel to the illuminating laser light in order to simplify analysis of the resulting fringe pattern. Force levels were varied in preliminary experiments and low force levels were found to be adequate for detection with the highly sensitive holographic method. These force levels are also satisfactory for future clinical investigations. An initial force was applied in order to overcome any initial displacements in the experimental equipment (eg. due to the tolerances inherent in the screw-lock system of D-bars). This basic force was experimentally measured to be 1.0 N for one end screw-vice fixation and 3.0 N for two-edged support. The bars were then deflected by additional force application. These »working» forces were determined to be 0.3 N and 1.0 N for one end screw-vice fixation and 1.5 N for two edge support.

Registration, evaluation and documentation. About 170 holograms were recorded. Each hologram was registered by means

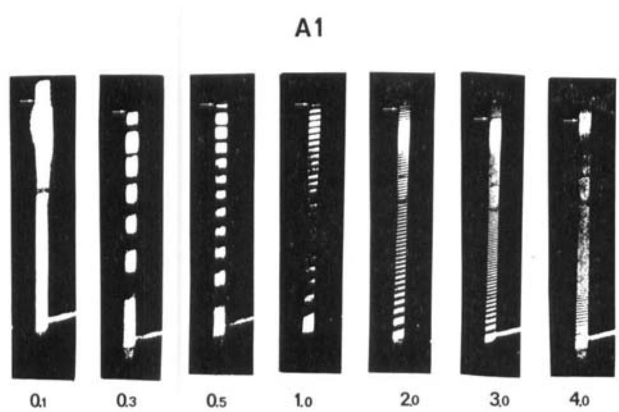

Fig. 7. Photographed reconstructions of holograms. Test bar A1 is in one end screw-vice fixation. Interference fringe pattern variations depend on forces. O.1 N — 4.0 N. The basic force level is 1.0 N. White arrows indicate the point of force application.

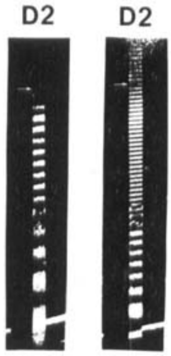

Fig. 8. Photographed reconstructions of holograms. Test bar D 2 is in one end screw-vice fixation. The between-exposure force application is 0.3 N (left); 1.0 N (right) and the basic force level is 1.0 N. The interference fringe pattern reveals a slight difference between the deflection of the proximal and the distal bar element depending on the screw-lock. White arrows indicate point of force application.

of double-exposure technique, developed and fixed. Reconstruction and evaluation was performed and photographs were made in a special photographic set up for the documentation of each reconstructed hologram. Some examples are shown in Figs. 7—11. The deflection in any point of the test bars could be determined.

The numbers of interference fringes in the holograms were recorded in tables

Fig. 9. Photographed reconstructions of holograms. Test bars D 1—D 4 are in a two-edge support. The between-exposure force application is 1.5 N. The basic force level is 3.0 N. White arrows indicate positions of the edge support.

Fig. 10. Photographed reconstructions of holograms. Test bars C 1—C 4 are on a two-edge support. The between-exposure force application is 1.5 N. The basic force level is 3.0 N. The interference fringe pattern reveals the deflection as well as a slight torsion within the bars during the experiment. White arrows indicate the positions of edge support.

and the corresponding deflection of the test specimens calculated by means of the formula $d = n \cdot k \cdot \frac{\lambda}{2}$

d being the deflection in μm
n » » number of interference fringes
k » » constant for the holodiagram
λ » » wave-length of the He-Ne-laser light

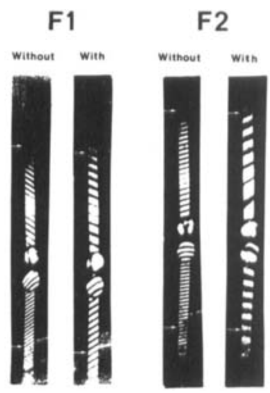

Fig. 11. Photographed reconstructions of holograms. Test bars F 1 and F 2 are without and with ivory cylinders on a two-edge support. The between-exposure force application is 1.5 N. The basic force level is 3.0 N. The interference fringe pattern reveals the difference due to rigidity depending on the experimental conditions. White arrows indicate the positions of edge support.

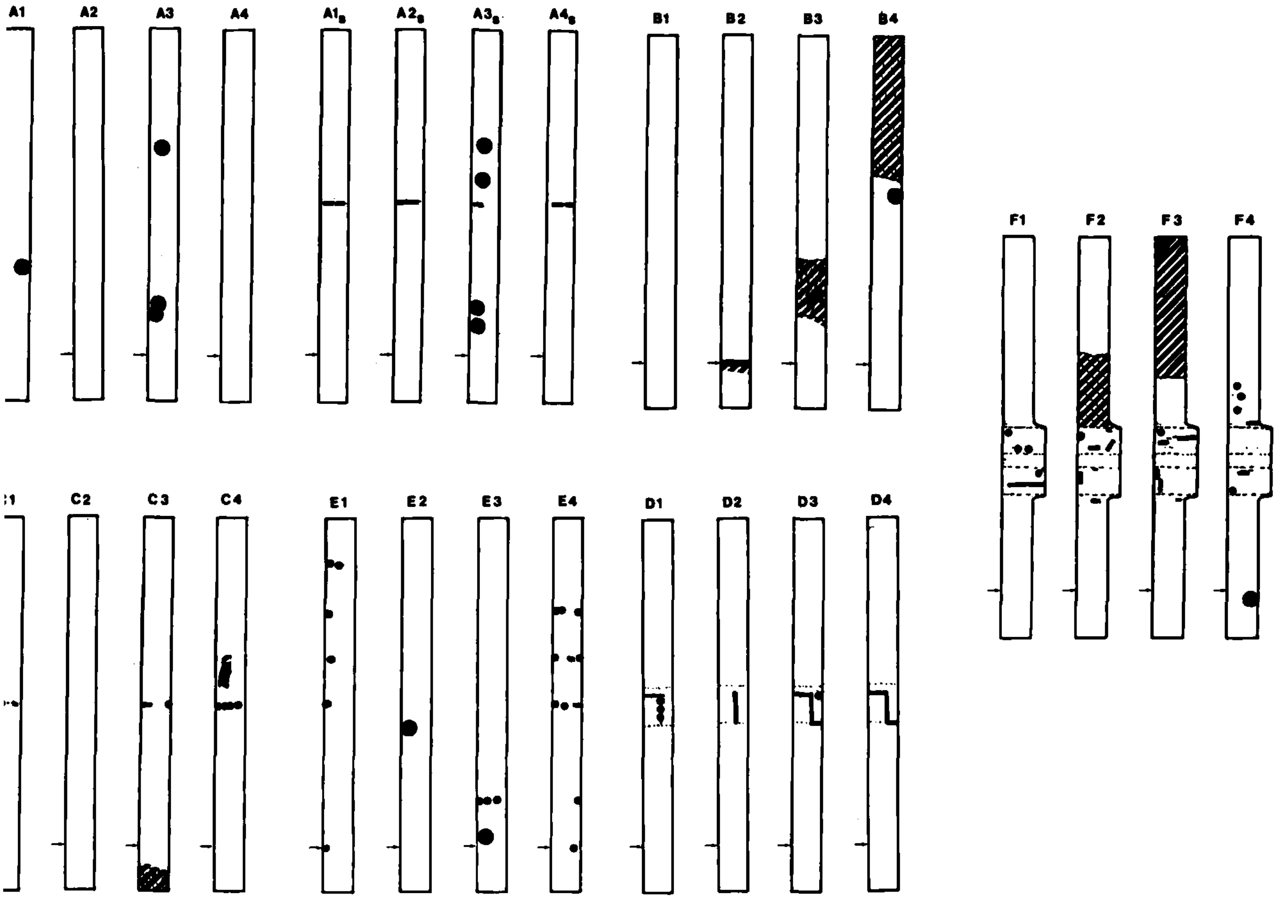

Fig. 12. Roentgenological findings in total survey. Black spots indicate small cavities within the bar material. Hatched areas indicate diffuse regions of reduced density.
Casting Method I: A1—A4; $A1_S$—$A4_S$; E1—E4;
Casting Method II: B1—B4; C1—C4; D1—D4; F1—F4
Arrows indicate the level of one end screw-vice fixation.

The deflection of each test bar at the point of force application at different force levels was visualized in plain histograms. Special calculations were made concerning the correct degree of deflection of bars on two-edge support considering the slight torsion within the bars during the experiments.

Radiographic findings

A survey of the radiographic findings with regard to the position of the defects and areas of reduced density in the bars is seen in Fig. 12. Defects were mainly found in the soldered joints. Areas of reduced density were recorded in bars, which were manufactured according to casting method II. The conventional casting technique proved to be superior as seen in the radiographic survey.

Holographic interferometry findings

The histograms were combined into three-dimensional histograms of total survey (Figs. 13 & 14). Deflection values for all test bars were calculated in relation to the

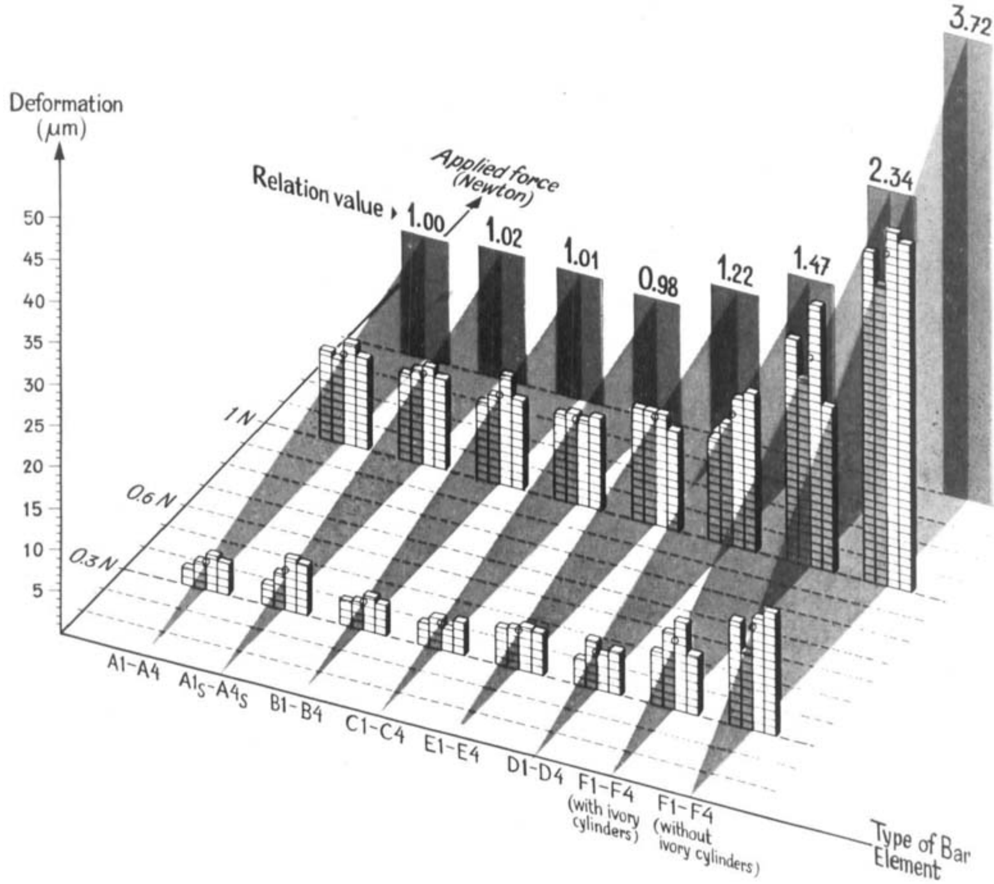

Fig. 13. Three-dimensional histogram of total survey concerning the elastic deformation of the test objects. One end screw-vice fixation. Basic force level 1.0 N.

A-bars in order to facilitate interpretation. (Relation values in the histograms).

Within each group variations were found, probably depending on the manual laboratory technique (waxing up, casting, soldering) and the experimental technique. At the lowest force levels (0.3 N) no conclusive effect from diffuse density reduction could be recorded. Note, however, the slight increase in deflection of A 3. (Fig. 13.) Localized defects in the form of three cavities were recorded within the gold structure of A3. (Fig. 12). Generally, the deflection at higher force levels (1.0 N and 1.5 N) seems to increase in defective bars. This was determined by comparing radiographic findings with the histograms.

The bars D and F being composed of different types of elements (screw-locks, hollow cylinders) showed the greatest variations within the group.

The number of soldered joints seemed to increase the deflection. This could be seen by comparing E1—E4 with $A1_s$—$A4_s$. (Fig. 13.)

Very small variations were found in one end screw-vice fixation between solid bars and bars having only one soldered joint. This could be seen by comparing A1–A4, $A1_s$–$A4_s$, B1–B4, C1–C4.

Note the slight increase of the relation

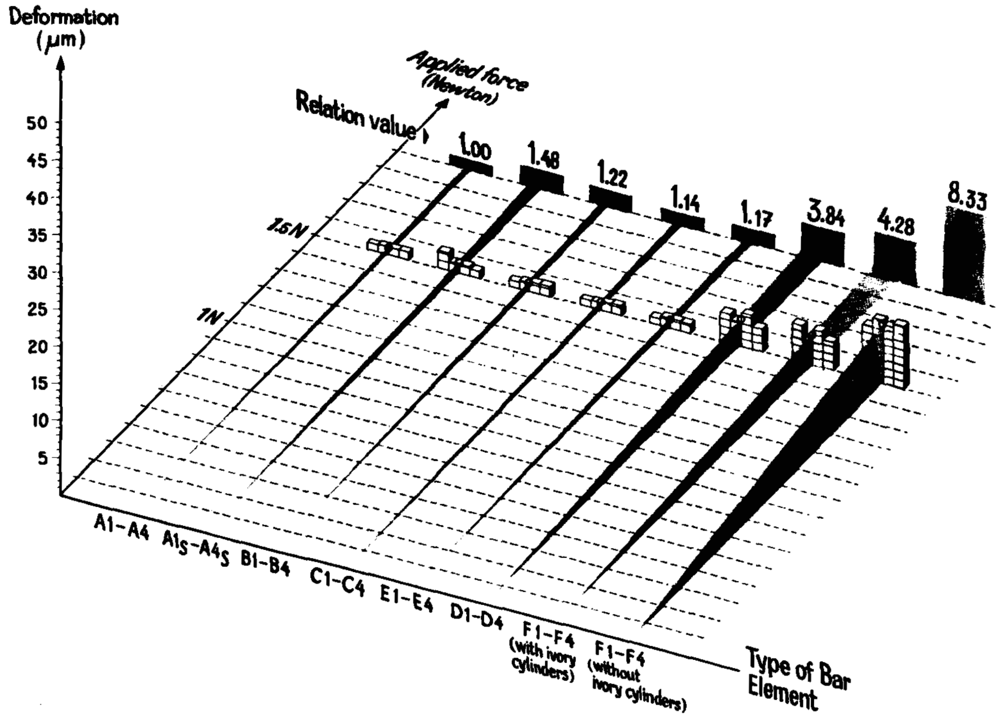

Fig. 14. Three-dimensional histogram of total survey concerning the elastic deformation of the test objects. Two-edge support. Basic force level 3.0 N.

value from 1.00 to 1.02 from A1—A4 to $A1_s$—$A4_s$ caused by cutting and soldering (Fig. 13).

On two-edge support the bar $A1_s$ was deflected more than double as much as the bar $A4_s$ giving an extremely high relation value for the group. This might depend on the defects in the soldered joint, the working force being applied on the joint. The basic force is 3.0 N in this experiment compared with 1.0 N in one end screw-vice fixation.

It was observed that the two-edge support could cause a slight torsion within the bars due to the unavoidable surface variations — a result of the manual laboratory technique. The torsion was visible as a bending of the holographic interference fringe patterns when the applied force was increased. The stiffening effect of the internal ivory cylinder was clearly proved in the experiments F1—F4 with and without cylinders.

DISCUSSION

The standard technique formula for mechanical strength investigation of rectangular section test bars in one-end screw-vice fixation is (*Ryder*, 1969)

$$d = \frac{P \cdot L^3 \cdot 4}{E \cdot b \cdot h^3}$$

d being the deformation (= the deflection of the bar surface at the point of force application)
P being the applied force
L being the distance between the point of force application and the level of the screw-vice
E being the modulus of elasticity of the bar material
b being the width of the bar

h being the height of the bar

The formula for bars on two-edge support with force application equidistant from the edges is

$$d = \frac{P \cdot L^3}{4 \cdot E \cdot b \cdot h^3}$$

L being the distance between the two supporting edges.

A comparison between the formulas implies that a certain force applied on a bar will deflect the bar 16 times more in one-end fixation than on two-edge support.

The clinical equivalence is as earlier described the deflection of extensive and intermediary pontics of fixed bridge-work, respectively, during mastication.

In the present investigation very low force levels were used. The bars were constructed with dimensions corresponding to average crown length, the soldered joints having a standardized height of 6.5 mm and a width of 4.0 mm, which might be regarded as fairly strong joints compared with usual clinical conditions. The modulus of elasticity of Sjöding's C-gold alloy is appr. 9000 kp/mm² (*Sjöding*, 1970). Although varying degree of defects were detected in the radiographic control, these factors together gave a high degree of mechanical resistance in the simulator arrangement, which proved to be convenient for the sensitivity as well as the measuring range of the utilized measuring method. The results, collected in the two histograms (Figs 13 & 14) show considerable variations as regards the deflection.

The histograms and the radiographic survey provide a method of translating among the experimental parameters used in the present study. For example, it is possible via the histograms to relate any deflection to its corresponding force level and vice versa. The utility of this three dimensional display technique can also be appreciated by examining the relative movement and its corresponding force (and vice versa) for any point in the bridge structure. Clinical conditions are more complicated — eg. the scale of distances are generally much shorter than in the present fixation and support models. Nevertheless findings in the simulator tests can be translated to clinical conditions since the definition of the elastic deformation implies a linear relationship between the applied force and the resulting deformation. Moreover, it should be kept in mind that the low force levels used in this simulator investigation are realistic with reference to the masticatory system in the last phase of the chewing sequence. Therefore, at these force levels, the findings in the simulator study can be translated to certain clinical situations.

A further development of laser metrology tests in simulator arrangements would probably give results of interest within a wide range of research problems.

The resilience of the human periodontium *in vivo* is a factor of great importance for the function of fixed bridgework. In the present investigation the conclusions are strictly limited to the proceedings within the metal construction positioned in a laboratory bench installation. The functional deflection and the mobility pattern of fixed prosthodontic appliances combined with the functional mobility of the abutment teeth should be studied *in vivo* by means of specially developed methods.

Acknowledgements. The guidance and help of Professor B. Colding, director of the Laboratory and Professor S. G. Ericsson, director of the Department of Stomatognathic Physiology are gratefully acknowledged.

The authors are very much indebted to Mr. J. Österberg of the Technical X-ray Center for his particular radiographic examination of the test specimens and to Dr. N. Abramson for his support as regards the evaluation of the holograms.

They would also like to extend their appreciation to Mr. S. Kallin IBM for his valuable help regarding the construction of the histograms, and to Mr. H. Alfredsson and Mr. L. Niia for their hard and ambitious work during the experiments. Mr. S. Stenberg skillfully manufactured the test specimens. J. Sjöding & Co supplied with the gold, the gold alloy solder and the precision locks.

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