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HOLOGRAPHIC INTERFERENCE AS A MEANS FOR QUALITY DETERMINATION OF ADHESIVE BONDED METAL JOINTS

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HOLOGRAPHIC INTERFERENCE AS A MEANS FOR QUALITY DETERMINATION OF ADHESIVE BONDED METAL JOINTS.

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Abstract

The nature of adhesive bonded joints implies that an opinion about their quality must be based primarily on non-destructive methods. The most effective of these methods are those that are based on measurement of the stiffness properties of the cured adhesive layer with help of acoustic means. The main drawback of these methods is the fact that they measure this quality only locally and in a rather time consuming way. Holographic Interference is a method that allows to measure deformations over larger surface areas simultaneously perpendicularly to that surface and with a magnitude in the order of a quarter wave length of light (approx. 1500 Ångström 0,15 μm) and even smaller.
In order to apply this method succesfully on adhesive bonded structures the metal surfaces of the areas to be detected must be moved into the direction of the observer over that minimum distance such as to become visible. For sandwich structures with their rather small skin thicknesses such deformations can be attained without many problems by means of thermal and vibration methods not only in case of voids but also in case of insufficient filleting of the adhesive between cellwalls and skin. In case of metal-to-metal joints with their small gluelayer thicknesses of 0,1 to 0,4 mm the required forces for creation of visible deformation would for some adhesives be impracticably high for detection of more quality information than the location of pure voids.
Therefore a method was developed using the deformation characteristics of the sheet adjacent to the bond as a bondquality parameter. This paper deals with investigations about the sensitivity of the holographic interference method for bondquality determination and gives information for a more efficient use of this method for production testing.

I Introduction

Among the numerous reports about the possible use of the Holographic Interference method that appeared since 1969 several papers indicated that one of the first practicable applications seemed to be the inspection of adhesive bonded components, such as used in the aerospace industry [1,2,3]. For introduction of such a new non-destructive quality control method, however, the following questions have to be answered:

1. Which kind of quality defects can be detected in both metal-to-core sandwich as well as metal-to-metal bonded joints?
2. What is the accuracy of this quality detection?
3. What are the capabilities of the new method for practical production testing?

The subject study was aimed at obtaining preliminary answers to these questions.

II Problem Definition

Holographic Interference (H.I.) is seen as a method that eventually could be used as a replacement for, or an addition to, the current methods of non-destructive inspection of adhesive bonded structures that are applied before these components are released for further production assembly. These methods are testing systems based on the resonance principle, such as the Fokker Bond Tester, or on the ultrasonic pulse-echo or through-transmission techniques of which several varieties are in practical operation. The first mentioned method is typically used for quantitative quality assessment whereas the other methods are qualitative methods used for detection of void or porous bondareas. H.I. is a rather sensitive method for the detection of objectsurface displacement, primarily in the direction of the observation. It is based on interference of the holographically reconstructed image with the real image of the same surface. As a result of this, interference patterns of light and dark zônes, so-called fringes, can be seen. (Fig. 1). Displacement of the objectsurface in the direction of observation in the order of at least 0,1 wavelength (0,06 μm) becomes visible due to distortion of the regular interference pattern. [4]. Transformation of a light area into a completely dark area occurs at a displacement of one half wavelength of 6328 Å or approx. 0,3 μm. From this information can be understood that substandard qualities in bonded structures can be made visible by means of holographic interference when it will be prossible to displace the bonded component on the side of the observer at the location of the substandard area at least 0,06 μm but preferably 0,3 μm relatively to the undeformed state. Whether the H.I.-method will be succesful or not, depends among others from the dimensions of the components, the mechanical properties of the adhesive used and the quality level at which a visible interference anomaly is required.

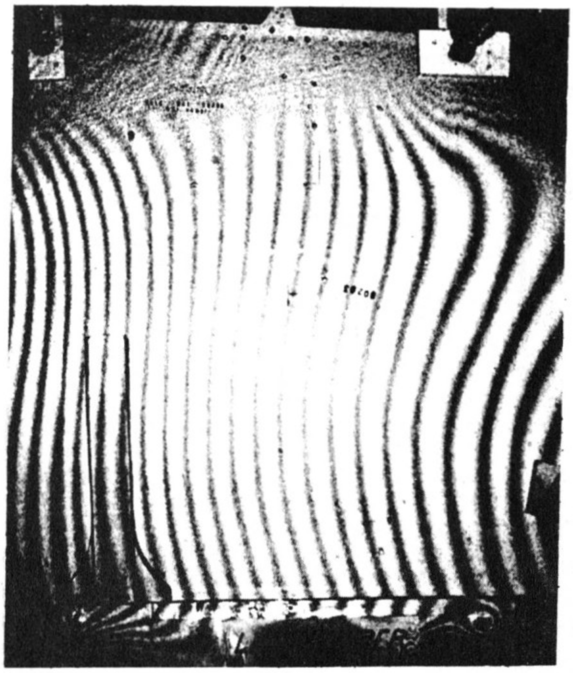

Fig. 1. Interference pattern of holographic image with its original objectsurface.

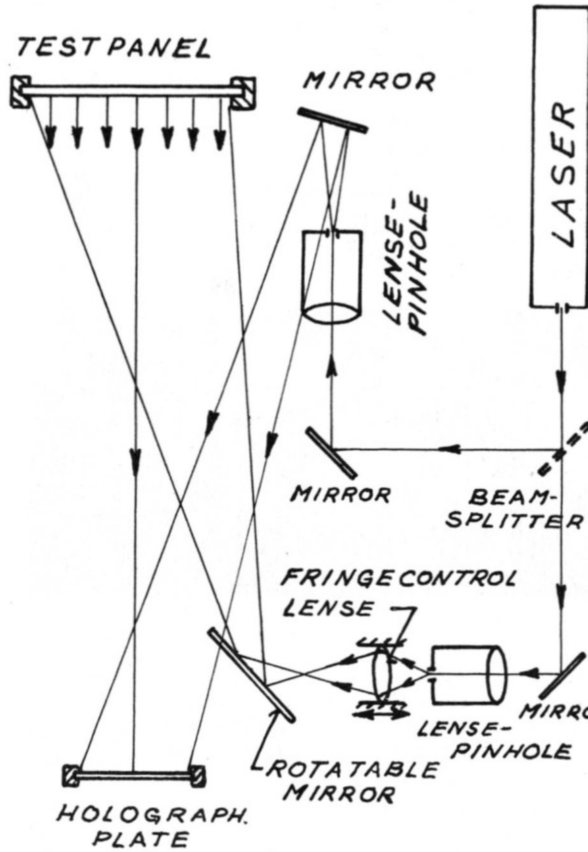

Fig. 3. Optical arrangement for Holographic Interference (H.I.) analysis of adhesive bonded panels using an axially movable lense system for optimization of the fringe pattern.

Cohesion Quality %	Glueline Thickness	adhesive Tensile Modulus* kgf/cm²			
		100.000	50.000	10.000	1000
90	100	54	27	5,4	0,54
70	100	42	21	4.2	0,42
	150	31,5	16	3.2	0,32
50	100	30	15	3.0	0,30
	200	15	7,5	1.5	0,15
25	100	15	7,5	1.5	0,15
	400	3,75	1.9	0,375	0,0375
Fig.2	μm	Min. Required tensile stress (kgf/cm²) for H.I. visibility			

* Modulus perpendicular to gluelayer

Fig. 2. Minimum tensile stresses required to obtain an holographically visible displacement for adhesive layers of various young's moduli, thicknesses and cohesion quality.

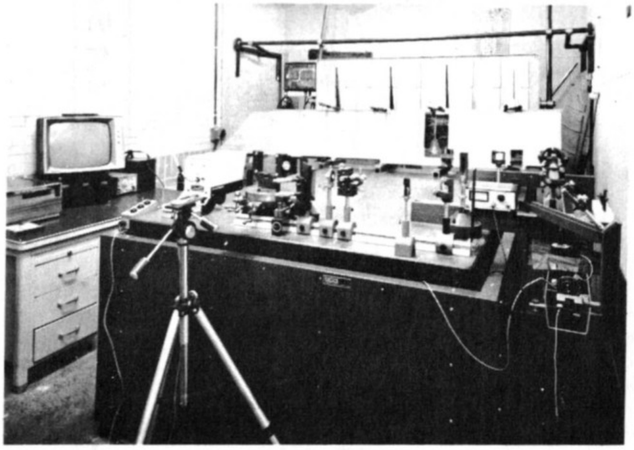

Fig. 4. Laboratory set-up for holographic analysis of adhesive bonded structures, using short circuit T.V. equipment with videorecording for ease of observation.

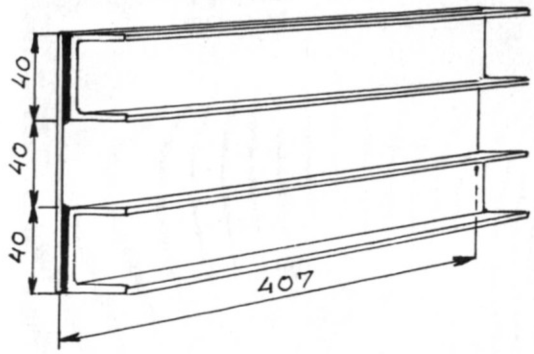

Fig. 6. Special metal-to-metal bonded panel for investigation of the bond quality influence on the membrane resonance characteristics of the interbond membranes.
Skin thickness 1mm.
Profile thickness 2,5 mm.

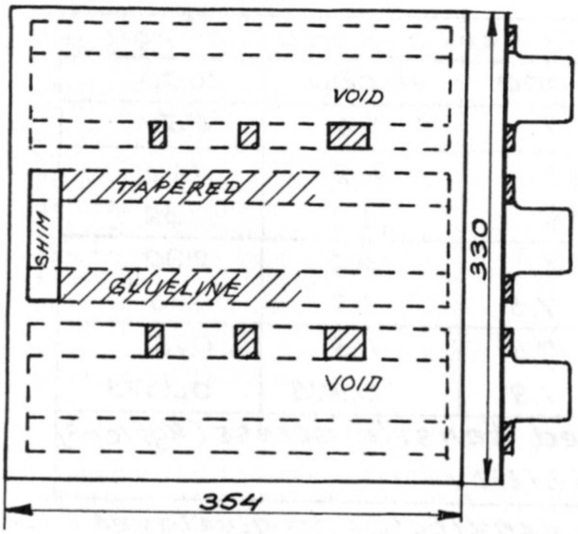

Fig. 5. Stringer-to-skin panel with typical built-in bond defects. Thickness of profile 1,5 mm; skins 0,4; 0,8; 1,0; 1,2 mm.

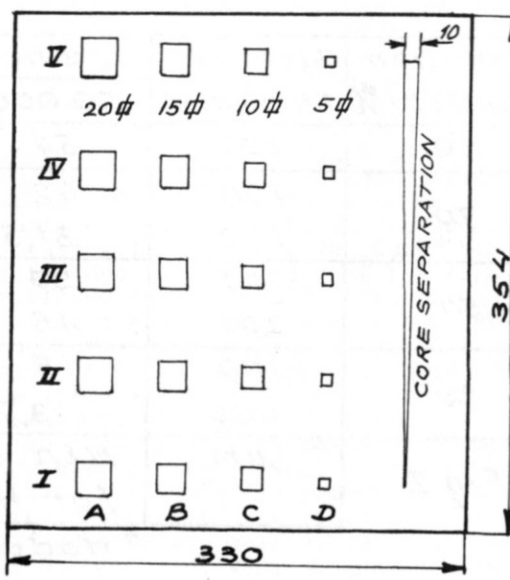

Fig. 7. Sandwich panel with built-in defects. Facethickness 0,3; 0,6; 1,0; 1,2 and 1,5 mm.
Honeycomb core celldiam. 4 mm Ø, foilthickness 0,04 mm.

Fortunatedly the cohesion strength of a cured adhesive layer is closely related with its Youngs' Modulus of Elasticity due to the fact that the curing parameters about equally affect the strength and the stiffness of these materials. Table 2 shows the minimum tensile stresses required on adhesive layers of various moduli in order to obtain a holographically visible displacement with various cohesion qualities and layer thicknesses. It is a known fact that in actual practise lower cohesion quality very often coincides with thicker adhesive layers. The stress values of table 2 are based on the smallest possible visible displacement of 0,06 μm (0,6 x 10^{-5} cm).
This table neglects the stress required to deform the metal topsheet for obtaining the required minimum visible deformation. Table 2 learns, however, that detection of thick porous bondareas in the lowest moduli range requires very small stresses in the order of 0,04 kg/cm^2 to be detectable as an anomaly in the holographic interference pattern.
Current 120°C curing modified epoxy adhesives with a modulus in the order of 50.000 kgf/cm^2 (perpendicular to the gluelayer) require for visibility of areas with 25% cohesion quality or less between 1,9 and 7,5 kgf/cm^2 for 400 and 100 μm gluelayerthicknesses respectively. Detection of quality levels of 25% and lower for practical purposes must be considered insufficient, as in many cases 50% quality areas must be detected, also in heavily loaded metal-to-metal bonded joints. So, it appears at first sight that for the current kinds of structural adhesives the H.I.-method will be limited to detection of pure voids and porosities in metal-to-metal joints as well as voids and irregularities in sandwich structures; as in those cases the topsheet can be lifted without much force. The testprograms discussed in the following were directed to finding the sensitivity of the H.I. method when using various methods of deformation. During these tests it was discovered that another method still opened the possibility of actual assessment of certain metal-to-metal bonded joints avoiding the otherwise required high intensity loading as discussed before.

III The Equipment

The holographic experiments were carried out with help of the optical equipment as schematically shown in Fig. 3. Initially a 15 m Watt and later a 50 m Watt Spectra Physics Helium-Neon laser was used. The illumination beam was provided with an axially adjustable lense system for optimization of the interference fringe spacing, compensating any change in distance between object and holographic plate. The object illumination mirror was fully adjustable in order to allow for a complete scanning of the surface to be inspected by the most sensitive area of the interference pattern, the so-called "Bull's eye". All optical equipment was mounted with help of optical rails and magnetical clamps to a heavy meehanite steel flattable, supported by means of an inflatable bag on top of a brickbed in order to eliminate interference from foreign vibrations as much as possible. All holograms were made with 4 x 5 inch Gevaert Scientia 10E75 plates. Deformation of the testpanels was created either by thermal stresses or vibrations. Heating was provided by means of a battery of ceramic infra red elements of 6 x 24 cm and 250 Watt each. Specially optimized bariumtitanate ceramic waver transducers with balanced steel and magnesium end-loads were used for obtaining the highest possible power out off the 50 Watt Kronhite amplifier and the Wavetek oscillator, in particular at frequencies up to 100 Kc. Fig. 4 shows the general arrangement for the tests including a short circuit T.V. arrangement with a monitor for observation and a video tape recorder for recording and repeated viewing of the real time deformation and resonance patterns. The use of the T.V. monitor considerably facilitated the observation of the hologram by more than one person. Furthermore the tuning for contrast and brightness gives an extra capability for adjustment of the highest possible sensitivity. Finally the possibility existed switching the black and white signals between the T.V. camera and the monitor that sometimes gave a better anomaly detection in the fringe pattern. The T.V. camera was equiped with a powerful zoomlense that allowed to inspect each fringe anomaly area in detail during the viewing. All of these inspectionphases were simultaneously recorded on the video tape.

IV Specimenconfigurations

Metal-to-metal bonded specimens

Metal-to-metal bonded specimens were made both as metal laminates and stringer-to-skin panels.

- Metal laminates were made of 0.8 + 0.8 mm and 1,2 + 1,2 mm dural 2024-T3 sheets bonded either with phenol-vinyl Redux 775 liquid/powder adhesive or with modified epoxy film adhesive FM 123-5 such that a variable bond quality was achieved due to the introduction of shims in the bondline.
- Stringer-to-skin panels were made of the types A and B, shown respectively in Fig. 5 and 6. The type A specimens were made off 1,5 mm thick ⊓ stringers and skins of 0,4; 0,8; 1,0 and 1,2 mm thickness. The bonds were manufactured with either constant quality but for local complete voidareas of widths of approx. 10; 20 and 30 mm or a variable quality from 90% to 0% due to shimming of the bondline. In the latter case only FM 123-5 was used.

The type B specimens consisted off 1 mm thick 2024-T3 clad skin panels on which 2,5 mm thick ⊔ -type stringers were bonded with their webs and their flanges perpendicular to the skin. These specimens were carefully produced at a number of different glueline qualities but being constant per specimen. The actual glueline quality was verified by means of the Fokker Bond Tester. The type B specimens were typically used for study of the resonance characteristics of the interbond free skin membranes under influence of the various adjacent bond qualities.

. Sandwich panels. Evaluation panels were made according to the configuration shown in Fig. 7 with face thicknesses of 0,3; 0,6; 0,8; 1,0; 1,2 and 1,5 mm material 2024-T3 alclad aluminium honeycomb 4 mm Ø cellsize and foilthickness 0,04 mm, height 35 mm. Adhesive used was FM 123-5 plus primer BR 127. Under the top faces defects were made as follows:

. Dimensions:
  5 x 5; 10 x 10; 15 x 15 and 20 x 20 mm
. Type of defect:
  I No adhesive film, no primer on sheet
  II No adhesive film, with primer on sheet
  III Protective plastic cover film between adhesive film and core
  IV Protective plastic cover film between adhesive film and face sheet
  V Crushed honeycomb depth 0,4 mm
  VI Honeycomb separation tapered from a width of 10 mm to 0

All panels were non-destructively inspected with help of the Fokker Bond Tester prior to the holographic inspection. It was noticed however, that by the heating or vibrations during the holographic experiments certain rather weak areas were entirely delaminated. In addition to the specially manufactured sandwichpanels several production components in which defects had been found by other means were holographically inspected.

V Holographic Interference Testresults with the thermal deformation method

Metal-to-metal bonded structures

The experiments with thermal deformation of the metal-to-metal bonded specimens of all configurations must be qualified as unsatisfactory. The main reason for these disappointing results is the fact that the metal-to-metal bonded panels, due to the thermal effects bend much more as a whole than local displacement perpendicular to the skin is created. The fringe pattern, as a result of this, becomes a very close spacing and defects remain practically invisible. It must be concluded that for metal-to-metal bonded structures both the skin-doubler as the skin-stringer configuration, there will be for the time being little hope for a succesful H.I. inspection of the bondquality when thermal methods are used.

Sandwich structures

The sandwich panels were tested with help of the Fokker Bond Tester Model 70, (Fig. 8) before the H.I. inspection, in order to check if substandard areas had been realized. Table 9 shows the Bond Tester B-scale acceptance limits that were applied for checking the actual quality status of the bonds in the defect-areas.

In table 10 the H.I. and the Bond Tester defectindications are shown. The latter are shown between brackets. The detected defect length of the core splice is indicated as a percentage of the total splicelength.

After the Bond Tester inspection the testpanels were mounted firmly on a welded tubular frame and subsequently heated from the rear for a period of 1 to 4 minutes based on the facethickness of the panels. From a practical point of view it appeared as most handy to make the hologram first of the product in the heated state. The defects then will become visible in the roomtemperature condition and they will remain visible as long as the panel is not heated again.

In the case the hologram, however, is made at roomtemperature then the defects only show up in the heated state. Their indication will disappear rapidly when the panel cools down to roomtemperature. Fig. 11 shows a typical photograph of one of the tested sandwichpanels. This, however, does not give a clear picture of what actually is seen during H.I.-inspection. Then the most sensitive "Bull's eye" area is scanning the panel when searching for defects. The testresults are summarized in table 12 for influence of face sheetthickness and kind of defect.

The general trend in the results shows slightly more defects detected by the holographic method. However, it should be noted that the Fokker Bond Tester readings were taken before heating the specimens as a result of which some of the low adhesion areas became full defects.

The following conclusions can be drawn from these thermal tests on sandwich panels:

1. There is a strong decline of the number of defects detected holographically at face sheetthicknesses of 1,5 mm.
2. The most realistic kind of defects I, II and V were about equally well detected by the H.I. and the resonance method.
3. The minimum size of detectable defect is for face sheets up to 1,5 mm 10 x 10 mm. For sheets thinner than 0,6 mm 5 x 5 mm defects are visible holographically.

VI Testresults of Holographic Interference with the vibrationmethod

Introduction

In par. I, it was already mentioned that based on theoretical considerations and the known mechanical properties of the cured adhesive materials with the present sensitivity of H.I. there is little hope for a complete quality determination of adhesive bonded joints by means of measurement of the thickness resonance characteristics. Recent publications indicated, however, that with the so-called "subfringe" technique displacement of an order of magnitude smaller than with usual H.I. technique will be measurable. These methods, that operate with either a frequency- or

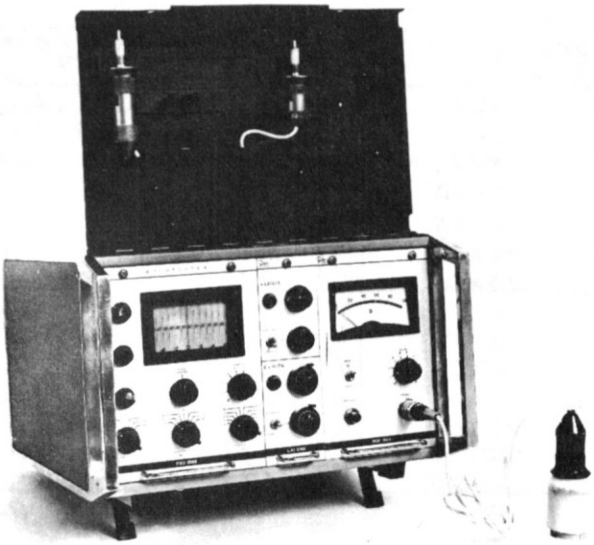

Fig. 8 . Fokker Bond Tester Model 70 used for quantative quality determination of the various bond areas.

sheet thickn. (mm)	FOKKER BONDTESTER Probe №	Acc. Limit
0.3	3414	B ≤ 75
0.6	3414	B ≤ 60
0.8	3414	B ≤ 55
1.0	1010	B ≤ 70
1.2	1010	B ≤ 70
1.5	1010	B ≤ 70

Fig. 9 . Acceptance limits used for defect determination with the Fokker Bond Tester.

sheet-thickness (mm)	DEFECT TYPE size	I	II	III	IV	V	% VI
0,3	A	+ (+)	+ (+)	+ (+)	+ (−)	+ (+)	
	B	+ (+)	+ (+)	+ (+)	+ (−)	+ (+)	90
	C	+ (+)	+ (+)	+ (−)	− (−)	+ (−)	(92)
	D	+ (+)	− (−)	− (−)	− (−)	− (−)	
0,6	A	+ (+)	+ (+)	+ (+)	+ (−)	− (−)	
	B	+ (+)	+ (+)	+ (+)	− (−)	+ (+)	80
	C	+ (+)	+ (+)	+ (−)	− (−)	+ (+)	(85)
	D	− (−)	− (−)	− (−)	− (+)	− (−)	
0,8	A	+ (+)	+ (+)	+ (+)	+ (+)	+ (+)	
	B	+ (+)	+ (+)	+ (+)	− (−)	+ (+)	70
	C	+ (+)	+ (+)	− (−)	− (−)	+ (+)	(75)
	D	− (−)	− (−)	− (−)	− (−)	− (−)	
1,0	A	+ (+)	+ (+)	+ (+)	− (−)	+ (+)	
	B	+ (+)	+ (+)	+ (−)	± (−)	+ (−)	60
	C	+ (+)	+ (+)	− (−)	− (−)	− (−)	(50)
	D	± (−)	± (−)	− (−)	− (−)	− (−)	
1,2	A	+ (+)	+ (+)	+ (−)	+ (−)	+ (+)	
	B	+ (+)	+ (+)	+ (−)	+ (−)	+ (+)	60
	C	+ (+)	+ (+)	− (−)	− (−)	+ (+)	(60)
	D	− (−)	− (−)	− (−)	− (−)	− (−)	
1,5	A	+ (+)	+ (+)	+ (+)	− (−)	± (+)	
	B	+ (+)	+ (+)	+ (+)	− (−)	− (+)	70
	C	+ (+)	+ (+)	− (+)	− (−)	− (+)	(50)
	D	− (−)	− (−)	− (−)	− (−)	− (−)	

CODE : + defect detected by H.I.
− ,, not ,, ,, ,,
(+) ,, ,, ,, B.T
(−) ,, not ,, ,, ,,

Fig. 10.Defects detected by means of Holographic Interference (H.I.) and the Bond Tester (B.T.)

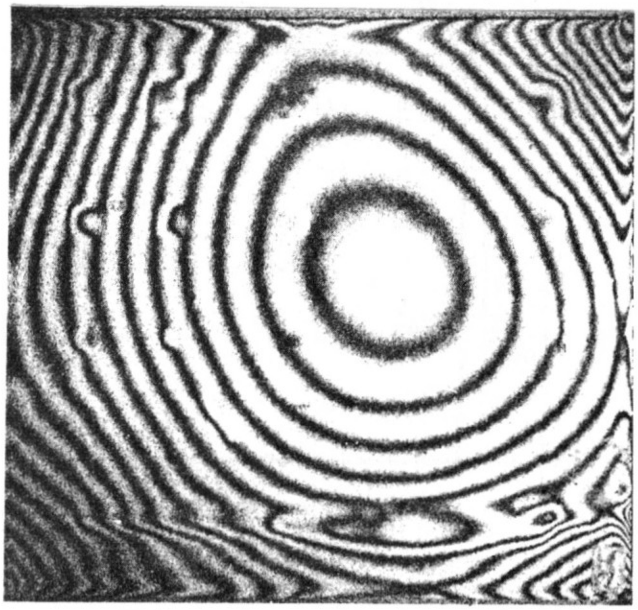

Fig. 11.Sandwich specimen during thermal deformation test (skinthickness 0,6 mm).

SPECIMEN CONFIGURAT.		NUMBER OF DEFECTS DETECTED		THEORETIC.
SHEET-THICKNESS [mm]	0,3	12	15(1?)	20
	0,6	11	12(1?)	20
	0,8	13	12	20
	1,0	8	10(3?)	20
	1,2	9	13(	20
	1,5	12	7(2?)	20
TYPE OF DEFECT	I	19	19	24
	II	19	19(1?)	24
	III	10	13(1?)	24
	IV	2	4(3?)	24
	V	15	14(1?)	24
SIZE OF DEFECT mmxmm	20x20	24	25(3?)	30
	15x15	22	24(2?)	30
	10x10	17	18	30
	5x5	2	2	30
		FOKKER BONDTESTER	HOLOGR. INTERFERENCE	INTENDED.

Fig. 12. Summary of defects detected in the sandwich specimens by either the thermal deformation H.I. method or the Fokker Bond Tester, based on the acceptance levels of Fig. 9

VOIDSIZE [mm x mm]		SHEETTHICKN. [mm] 0,4	0,8	1,0	1,2
3x3	CLAMPED	153	306	382	459
5x5		55	110	138	165
8x8		21	43	53	64
10x10		14	28	35	41
15x15		6,2	12,4	15,4	18,5
20x20		3,4	6,8	8,6	10,3
25x25		2,2	4,4	5,5	6,6
3x3	SIMPL. SUPP.	84	168	210	270
5x5		30	61	76	91
8x8		12	24	29	35
10x10		7,7	15	19	23
15x15		3,4	6,8	8,5	10,2
20x20		1,9	3,7	4,7	5,7
25x25		1,2	2,4	3,0	3,6

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Fig. 13. Calculated fundamental resonance frequencies for rigidly clamped 2024-T3 square membranes of various thicknesses.

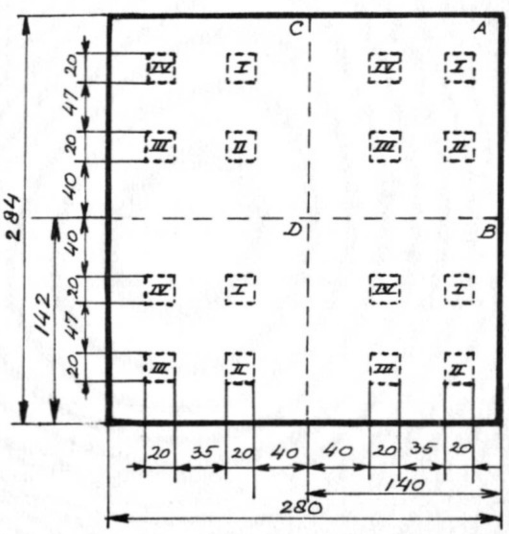

Fig. 14. Special sandwich panel for resonance testing facethickness 0,4 mm. Honeycomb core 24 mm thick.
Section A cell Ø 3 mm; foil 0,050 mm
Section B cell Ø 6 mm; foil 0,040 mm
Section C cell Ø 4 mm; foil 0,050 mm
Section D cell Ø 4 mm; foil 0,040 mm
Defect type I: no core-no adhesive
Defect type II: no core
Defect type III: no adhesive
Defect type IV: crushed core

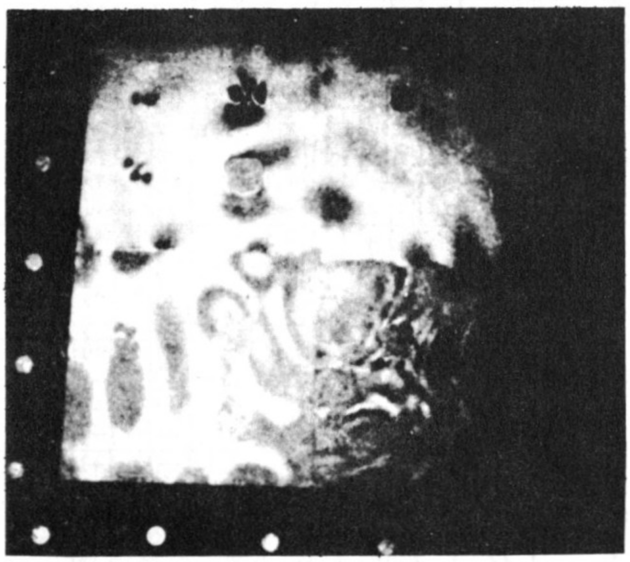

Fig. 15. Holographically detected resonance of the panel of Fig. 14 at 19 Kc.

a phase- modulated reference beam have allowed detection of object displacement in the order of 50 Ångstrom (0,05 μm) (5). In the subject program these new methods were not yet available and adhesive bond-quality determination therefore had to be limited to those of the membrane resonance nature with rather large amplitudes. In the near future these new techniques deserve to be explored for this purpose.
This report includes membrane resonance testresults on metal-to-core and metal-to-metal joints.
Assuming that at resonance condition the amplitude is of sufficient magnitude to allow for visibility of the high amplitude areas, membrane resonance tests can be used for quality determination of bonded joints as follows:

(1) For definition of the actual <u>size</u> of the free resonating membrane <u>that</u> can be the <u>not</u>-bonded area:
    (i) <u>within</u> the boudary of the planned <u>bond</u> surface and thus indicating voids in the bonds

    or

    (ii) <u>adjacent</u> to the bonded area, in-<u>dicating</u> void areas along the bond edges.
(2) For definition of the <u>frequency</u> and the <u>mode</u> of the membrane <u>resonance</u> of the <u>non</u>-bonded areas.
(3) For assessment of the <u>frequency</u> and <u>mode</u> of a membrane formed <u>by a</u> bonded <u>laminate</u> from which the stiffness characteristics of the composite as a whole can be deducted.

On all of the foregoing possibilities exploratory testwork has been carried out under this program.
The resonance frequencies of membranes are a function of:

. the membrane dimensions, including sheetthickness
. the type of membrane material
. the kind of clamping of the edges: simply supported or clamping with various degrees of rigidity.

So, when the membrane material and the thickness are given the resonance frequencies are indications for the membrane dimensions and or the clamping efficiency.
In the case of adhesive bonded structures both of these parameters are of interest for determination of the bondquality. As an orientation of the possibilities in Fig. 13 calculated fundamental resonance frequencies for square rigidly clamped and simply supported sheet elements are given. The voids in bonded structures must behave between simply supported and rigidly clamped membranes. Taking into account the realistic fact that with the available equipment frequencies of 100 Kc or higher could not be applied with sufficient energy to allow analysis of larger areas with the current H.I. method, it appears that the small voids of 3 x 3 mm may be detectable with the thinnest 0,4 mm sheet only; 5 x 5 mm squares will show visible resonance up to 0,8 mm sheetthickness, while from 8 x 8 mm and larger for all thicknesses from 0,4 to 1,2 mm visible resonance should occur.

It appears also that for the larger voids the fundamental resonance frequencies are that low in the sonic range that when for practical reasons low ultrasonic frequencies are chosen already higher order resonance modes will occur.
Based on these orientative calculations estimates could be made about the size of voids that would be detectable at various frequencies. Unknown, however, are the actual irregular shape of the voids and the clamping rigidity of the gluelayers surrounding the voids. The values given in table 13 therefore give only a very rough indication of what can be expected.

<u>Testresults on sandwichpanels</u>

In view of the very promising results of the, easy to perform, thermal tests on sandwich panels the resonance tests were restricted to checks with help of a special sandwich panel (Fig. 14) consisting of 0,4 mm skin and 25 mm thick honeycomb core devided in four sections of different density core, each containing four different rather course voids. A clear indication of the various defects were obtained at 16,5 Kc. Some of the entirely loose voids were then already resonating in the second mode. At 8 Kc some defects were already detected resonating in the fundamental mode. At 19 Kc the section with the lowest density core (cellsize 6 Ø mm, foil 0,04 mm) showed membrane resonance over the whole section.(Fig. 15)At 40 Kc in the same section clearly membrane resonance in the face of each individual cell was obtained. This was according the expectations, as Fig. 13 shows for a rigidly clamped square membrane of 5 x 5 mm a fundamental resonance frequency of 55 Kc and for 8 x 8 mm 21 Kc for this 0,4 mm face thickness.
The test proved the straightforward possibilities of the resonance test for sandwich structures following the expectations.

The problem areas are only on efficient excitationinstallation and the limited detectability of small voids under thicker face sheets. The thermal deformation method in this respect is more sensitive and therefore will be preferable for production test-installations for sandwichcomponents.

<u>Testresults on metal-to-metal specimens</u>

Initially all metal-to-metal specimens, laminates as well as ⊓ stringer-to-skin panels of the A-configurations, were analysed over the full frequency range up to 100 Kc and even higher. Also in this case the void areas followed the expectations given by Fig. 13. As soon as the resonance frequency of those areas of the skin that were insufficiently supported by the gluelayers was approached the resonancepatterns became visible. However, this happened only when the adhesion or cohesion strengths of the joints in that area were practically zero. Even a slight attachment of the skin was sufficient to prevent the occurrance of membrane resonance. As the vibration energy was too low to break up weak bonds, detection of substandard weak bonds

appeared to be rather ineffective.
During these studies of the various ⊓-stringer-to-skin panels it became clear, however, that a quite different aspect was worthwile for further exploration. That was the resonance behaviour of the skin-membrane areas between the bondareas. It appeared that resonance patterns of these non-bonded areas were clearly influenced by the quality of the surrounding bond-areas. In the case of the presence of voids in the bonded areas extending into the bondedges the effective width of the interbond fields were larger and as a result of this the various resonance modes then appeared at considerably lower frequencies than when these membranes had high quality bondareas as their boundaries. Fig. 16 shows a sequence of H.I. resonance patterns of panel I (skinthickness 0,4 mm). The interference hologram of Fig. 16a demonstrates that at a sonic frequency as low as 1 Kc voids in bondareas are indicated by bulges of the resonance patterns of the "interbond" skin fields into the bond areas. When the frequency was gradually increased, these void areas were always indicated by the fact that adjacent to lower quality areas at the bondedges at the fundamental resonance frequency for the other interbondmembranes, in these areas already higher modes of resonance were fully established. (Fig. 16b and c) These phenomena demonstrated themselves spectacularly with the panel V, that had for one half substandard bonds due to shimming of the bondlines and/or double or tripple bondfilms. It was the striking photograph of Fig. 17 that initiated the ideas that in this way a lead might be found towards the development of a proper quality detection system for metal-to-metal bonded structures by means of the resonance characteristics of adjacent skinmembranes.

Bonded membrane resonance studies

For this purpose panel type B was developed. For reasons of ease of manufacture and mounting for testing the ⊔-type sections were bonded with their webs on to the skin. The various bond qualities were achieved by shimming during cure. It was hoped that a correlation would be found between the resonance behaviour of the skin between the bonds and the bond quality, due to the fact that in case of simply supported membrane edges the effective width would be larger than in the case of rigidly clamped edges (see Fig. 18).
The obtained bond qualities for the type B panels 1 through 5 were resp. 43; 53; 62; 90 and 95% of the ideal quality of the FM 123-5/BR 127 bond.
In order to obtain better understanding of the resonance characteristics of such slender membranes between stiffener flanges calculations and H.I. analysis were made of similar 2024-T3 membranes 400 mm long, 40 mm wide and either simply supported along the edges or rigidly clamped.
It was found that the following formula described the resonance frequencies of these narrow skin membranes rather well:

$$f_{m,n} = \frac{\pi}{2}\sqrt{\frac{gD}{\rho t}}\left\{\left(\frac{m}{a}\right)^2+\left(\frac{n+C}{b}\right)^2\right\}$$

$f_{m,n}$: resonance frequency showing m half waves in length direction and n half wave lengths in width direction of the membrane.
a : membrane length
b : membrane width
t : membrane thickness
ρ : membrane density
D : bending stiffness of membrane defined as:

$$D=\frac{E.t^3}{12(1-\nu^2)}$$

ν : poisson ratio
C : clamping constant
The formula is based on simple support of the short edges of the membrane. In the case the long edges are also simply supported the value of the factor C is zero. For rigidly clamped long edges of the membrane C equals 0,25 and 0,75 respectively for odd and even numbers of n. The calculated characteristics of the clamped and simply supported membranes as shown in Fig. 19 were verified by means of H.I. analysis. It is typical that after an increasing number (m) of half wave lengths in the length direction of the membrane and one single half wave in the width direction (n=1) with increasing frequency the pattern suddenly changes into a pattern with two half waves in width direction (n=2) and a small number of m. The latter value increases again with increasing frequency after which the pattern changes again to a small number of m and n=3. This switch in resonance pattern occurs with the simply supported membranes at a significantly lower frequency than with the rigidly clamped membranes.
The bonded membranes could be expected to behave between the simply supported and the rigidly clamped membranes i.e. closer to the clamped ones with higher bond quality. With help of the type B panels, having various bond qualities, this was checked holographically.
It appeared indeed that the curves of the bonded membranes were well within the zônes with the simply supported and the clamped conditions as boundaries (Fig. 20) It appeared also that the differences in frequency between the occurrance of a certain resonance pattern in the various bond quality conditions became more clear with the higher frequencies. Particularly interesting appeared the frequencies at which the change-over from a high to a low m-value took place when changing from p.e. n=2 to n=3. This switch takes place at a lower frequency for a lower quality bond than with a higher quality one. In this way by a proper choice of frequency bond qualities could be separated by the presence or not of the n=3 configuration at a certain frequency. Fig. 21 gives a good example of such a condition. At 25,589 Kc the 43% bond showed already an n=4 condition the 95 bond quality still showing an n=3 condition

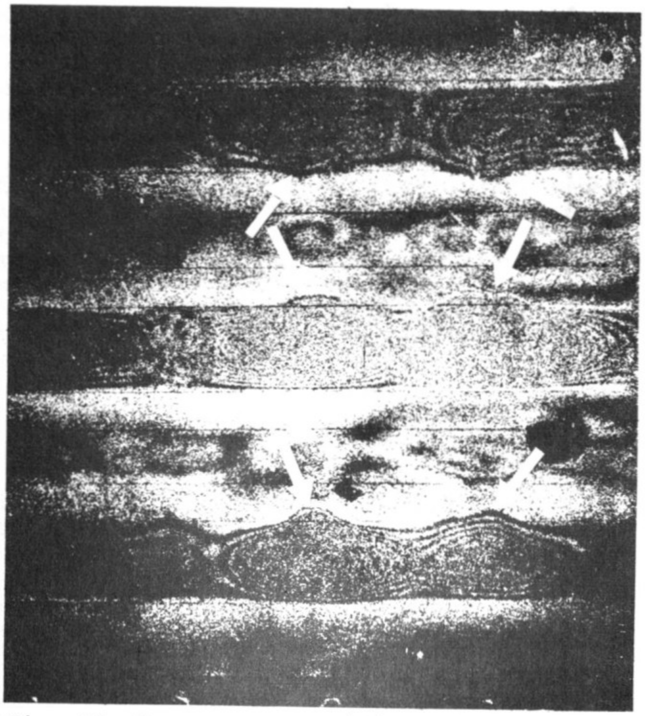

Fig. 16a. Resonance condition of stringer-to-skin panel I, skin thickness 0,4 mm at 1 Kc. Note the "bulges" in the interbond membranes indicating the location of voids in the bondedges.

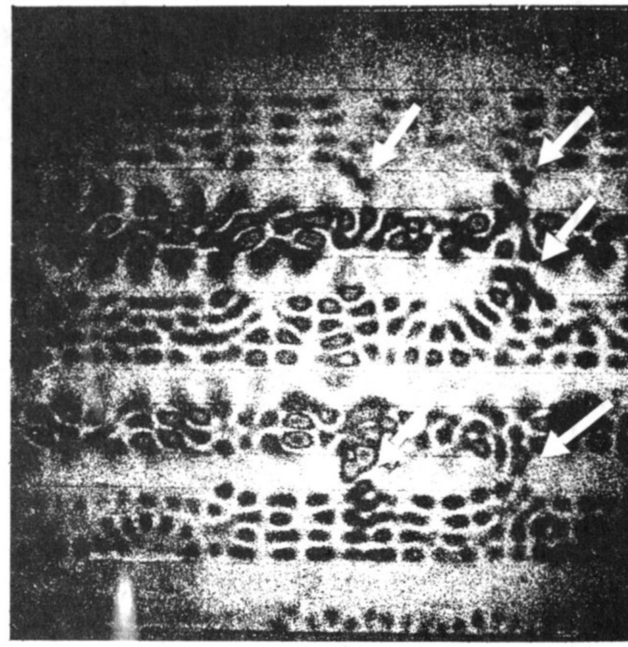

Fig. 16 c. Resonance condition of panel I at 13,5 Kc. Membrane resonance at bondvoids is visible.

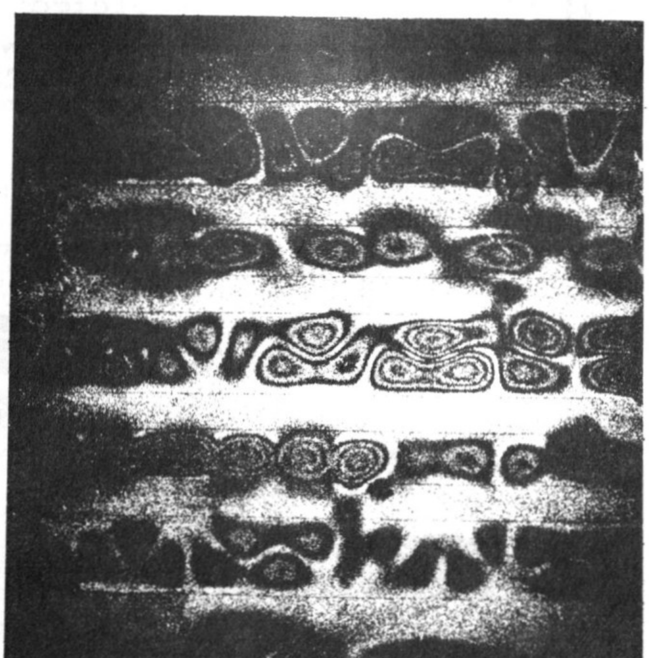

Fig. 16b. Resonance condition of panel I at 4 Kc. In the interbond membranes higher order resonance modes are visible adjacent to bondvoids.

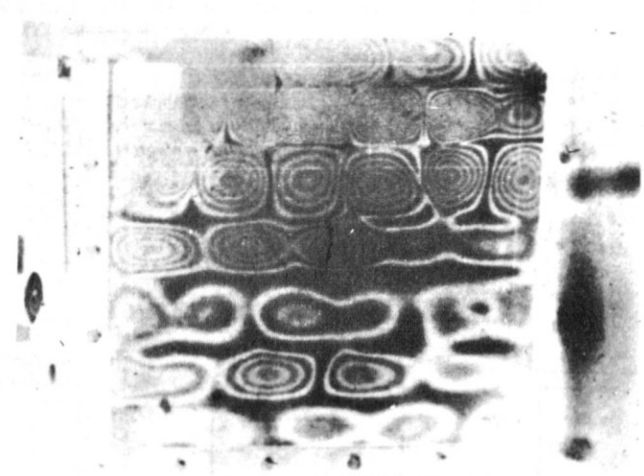

Fig. 17. Resonance condition of panel V having 1,2 mm skinthickness and thick gluelines in the upperpart of the panel.
At 3,6 Kc the low clamping efficiency of the low quality bonds is clearly shown by the interbond membrane resonance extending into the bondareas.

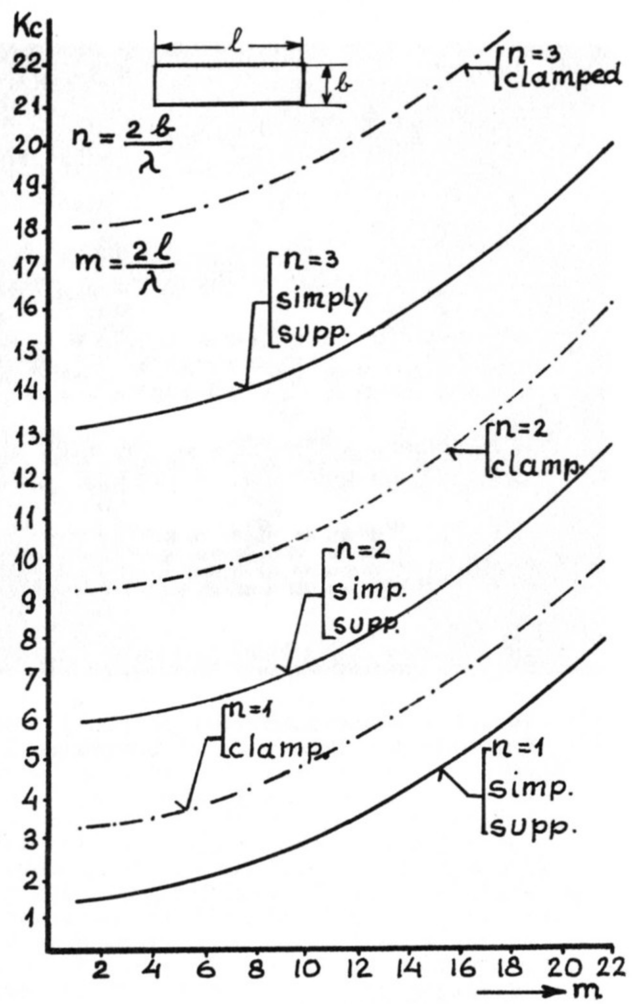

Fig. 19 Calculated resonance characteristics of slender membranes either clamped or simply supported along their long edges. Thickness 1 mm; material 2024-T3; width 40 mm.

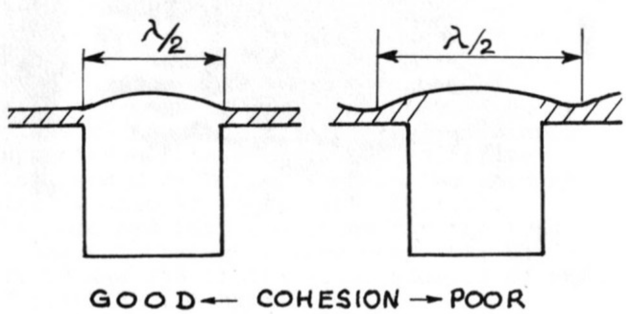

Fig. 18. Schematical demonstration of the influence of the difference in clamping efficiency by low and high quality bonds.

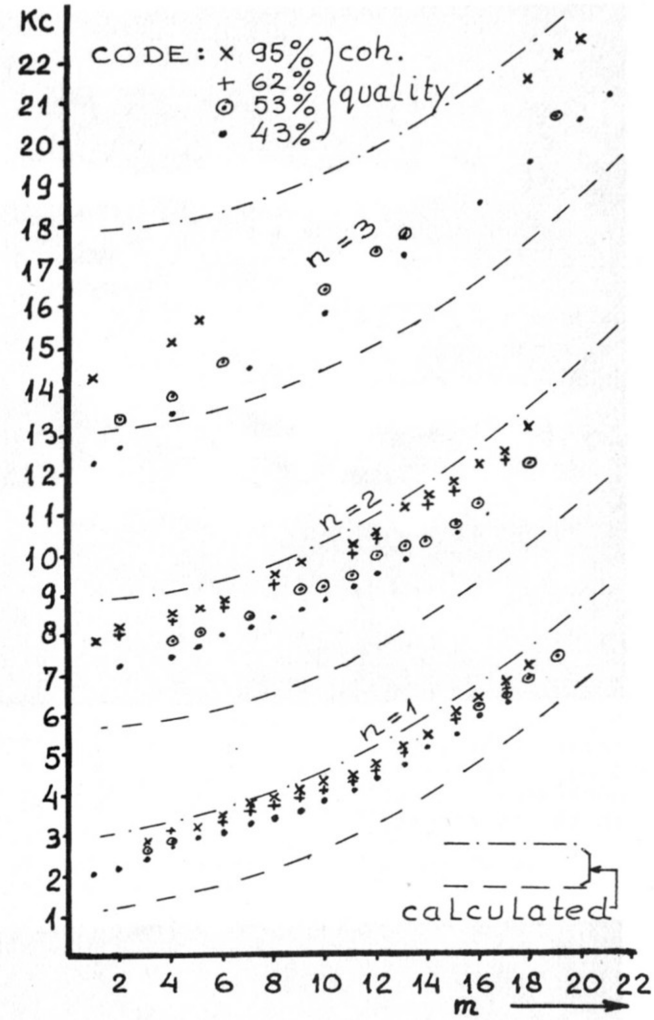

Fig. 20. Resonance characteristics, determined by holographical interference analysis of interbond membranes adjacent to 95% and 43% quality bonds.

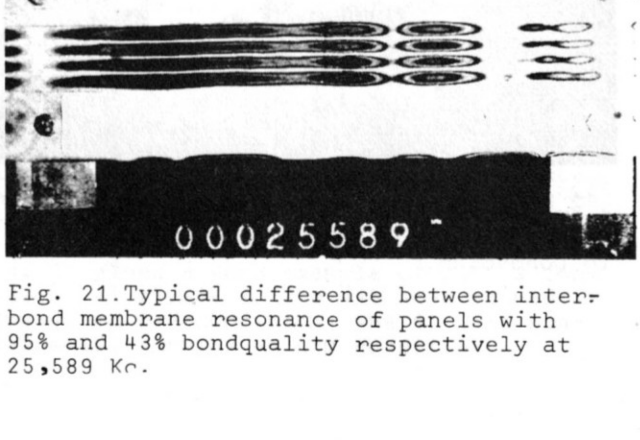

Fig. 21. Typical difference between interbond membrane resonance of panels with 95% and 43% bondquality respectively at 25,589 Kc.

The described membrane resonance program proved that the found phenomenon offers very interesting possibilities for quality determination of panels with bonded stiffeners. Future work will be directed to determination of the factor C for various qualities and adhesives in the membrane resonance formula. Important is that in this way a bond quality aspect is controled that is particularly important for the effectiveness of the bonded skinpanel as a structural component, as the clamping effects control the buckling behaviour of the panel under compression or shearloads.

VII Holographic Interference Testing of bonded components

At the end of this principle study inspection of full size panels was undertaken. In view of the favourable results with the thermal testing sandwich panels were analysed holographically as a prelude to actual introduction of holographic interference as an additional means for production quality control. It appeared that the method proved to be very effective. Not only the detection of poor core-to-skin bonds was performed with good results, but also hidden problems due to errors in honeycomb core machining were found. A clear impression of the quality of core splices could be obtained as well (Fig. 22).

VIII Conclusions

1. This study showed that holographic interference inspection of adhesive bonded components offers interesting perspectives as an addition to the inspection with current N.D.T. methods.
2. For sandwich components the thermal deformation method proved to be sufficiently effective. The effort required for vibration testing in that case is not worthwhile.
3. For metal-to-metal bonded joints the thermal deformation method has little future.
4. The method of resonance analysis of "interbond" membranes as a means for quality determination of bonded stringer flanges opens interesting possibilities for the future.
5. The holographic interference method is losing effectiveness with increasing skin thicknesses.
6. The use of T.V. equipment offers a great help for production testing installations for H.I. inspection.

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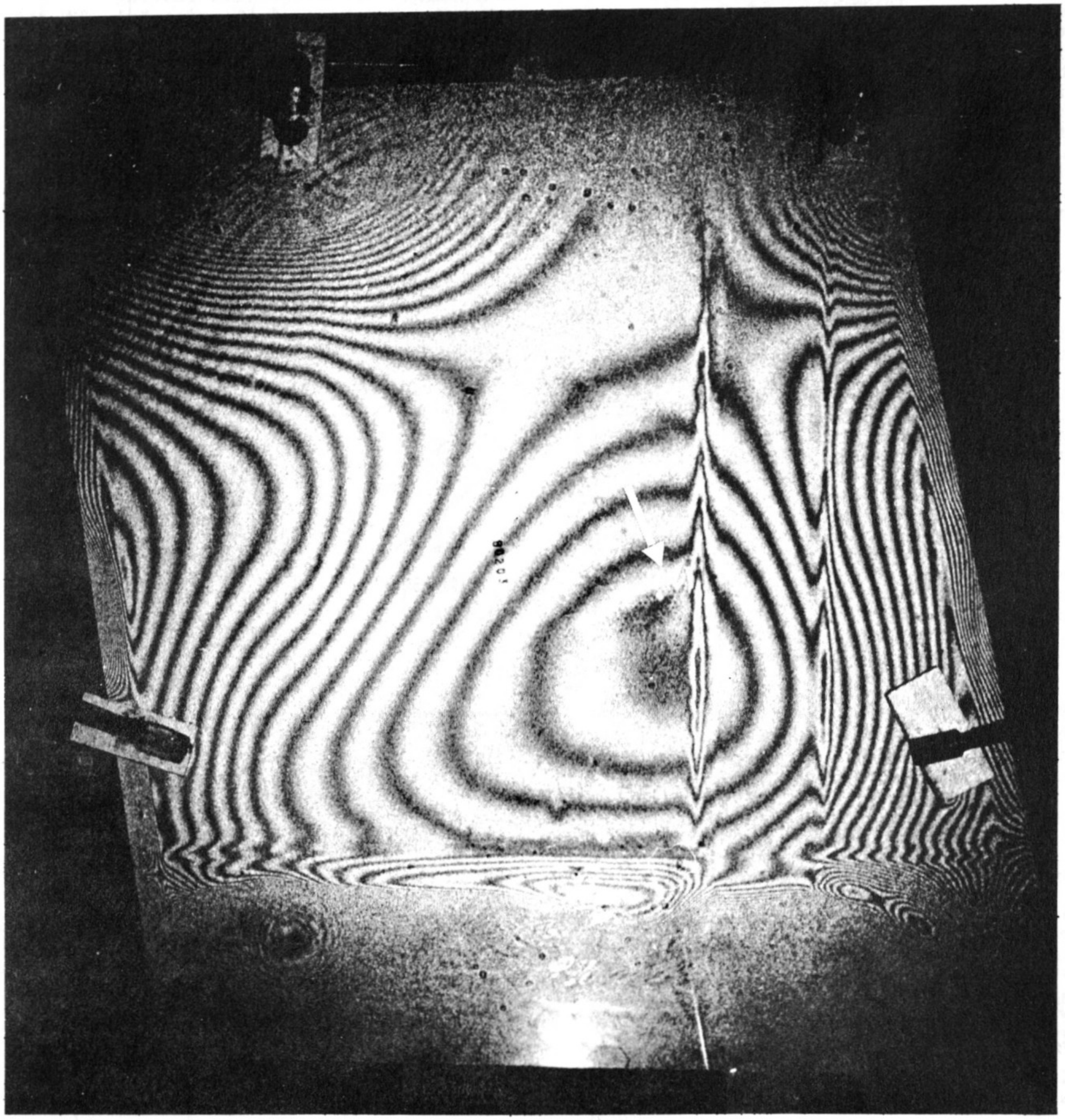

Fig. 22. Interferogram of fullscale sandwich component, showing a defect in the core splice.