

METHODS OF TESTING FOR ENDURANCE OF STRUCTURAL ELEMENTS USING SIMULATED ACOUSTIC LOADING

1. NOTATION

E	Young's modulus of elasticity	N/m ²	lbf/in ²
f_n	resonant frequency	Hz	Hz
H	height of stiffener (see Sketch 3.2)	m	in
L	skin or beam length (see Sketch 3.2)	m	in
N_r	equivalent endurance, taken as half number of zero-crossings to failure of stress-time function	cycles	cycles
S_m	mean static stress value	N/m ²	lbf/in ²
S_{rms}	root mean square value of dynamic stress	N/m ²	lbf/in ²
T	specimen thickness (see Sketch 3.2)	m	in
t	time	s	s
W	skin width (see Sketch 3.2)	m	in
ϵ_{rms}	root mean square value of dynamic strain	m/m	in/in

2. INTRODUCTION

This Item describes the specimens and test techniques used to determine the endurance of structural elements under simulated acoustic loading. The intention of these tests is to gather endurance data, in the form of S_{rms} or ϵ_{rms} versus N_r , to use for the prediction of acoustic fatigue life.

Structural elements or coupons, which are designed to represent features of the original, or parent, structure, are excited by narrow-band loading of random amplitude with zero mean load to simulate the stress or strain response due to acoustic loading. The means of excitation is generally an electro-dynamic vibrator, often termed a shaker.

This method of generating endurance data using coupon specimens has become accepted practice, especially when evaluating a number of candidate joint configurations. The alternative is the evaluation of acoustic fatigue life using one particular design configuration in a full-scale component or a number of large-scale panel specimens (including various structural variations) and testing in an acoustic fatigue siren facility. This is costly for specimens, test facility and test duration as testing to failure is required. The full-scale component or panel would be tested using a simulation of the actual noise environment to provide the correct structural response. This is usually broad band excitation although some noise sources can be narrow band, see Item No. 86025. However, the approach used by Items in Volume 3 of this Sub-series (Stress/strain response to acoustic loading) such as Item No. 67028 assumes a dominant single mode response for the prediction of fatigue life. The use of a specimen that responds in a uni-directional manner

Issued October 1993

1

has been found satisfactory to simulate the local bending response of a two-dimensional panel although special care is necessary with composite specimens.

Typical data obtained from tests conducted in this manner are presented in Item Nos 72015, 73010 and 84027. The majority of testing reported has been with respect to aerospace structures which are by necessity lightweight and hence susceptible to acoustic fatigue where subjected to high intensity noise sources, see Item No. 86025, Section 2. However, the general techniques described could be applicable to fabricated structures used in other industries.

The information presented here has been compiled from available sources, although much is unpublished, and is a consensus of the techniques employed since the early 1960s. The basic method has not changed greatly during this time although the control, recording and signal processing instrumentation has increased in accuracy, speed and sophistication. Therefore the techniques described in this Item should be regarded as a guide to the general accepted practices but other means should not necessarily be excluded if circumstances demand. More recently the use of composite structures has required increased research into their resistance to acoustic fatigue, see Derivation and References of Item No. 84027. In a metallic structure damage is usually shown by visible cracking in the material but in a composite structure damage could take other forms such as internal delamination and remain less obvious to visual inspection. In addition the basic fibre-reinforced composite construction lends itself to a multitude of variations in configuration due to fibre-resin systems, material lay-ups and manufacturing methods.

Section 3 describes the design considerations for a structural element in order to obtain a simulation for the response mode of the original (or parent) structure. A description of a wide range of element geometries is included with information as to the probable failure locations and any inherent specimen limitations. Typical sizes for the specimens are also included. The means for mounting these specimens are discussed with some examples for multiple specimen tests which enable a set of specimens to be tested at a given test level in order to allow for the scatter in fatigue life to be determined with a minimum elapsed test time. These design guidelines will allow for successful application to other structural configurations.

Section 4 provides guidelines on the methods that are adopted for conducting random vibration testing, including the excitation requirements, the measurement and monitoring instrumentation, and the assessment of structural damping and response linearity. The means of defining a failure situation for a specimen, so that the fatigue endurance may be determined, are presented and the use of residual strength assessment discussed. The application of these test techniques to provide endurance data at elevated temperatures is also addressed.

Section 5 provides guidance regarding the interpretation of the results from fatigue endurance tests under random vibration loading.

3. SPECIMEN DESIGN

The design configuration for a specimen used for random vibration fatigue testing is usually based on the type of structural joint or element being represented and a knowledge, or at least an estimation, of the probable failure or damage location. The estimation of this location may require an understanding of the structural response modes for the complete structure or component from which the joint configuration is extracted. The influence of the structural response modes in determining damage locations is discussed in Section 3.1 and some further explanation may be found in Item No. 86025.

Information for the design of different specimen types is given together with methods used for attaching the specimens to an electro-dynamic vibrator. Consideration is given to metallic and composite specimens as well as structural configurations such as honeycomb. Fatigue endurance data for some of the specimen types described are presented in Item Nos 72015, 73010 and 84027.

3.1 Response Modes

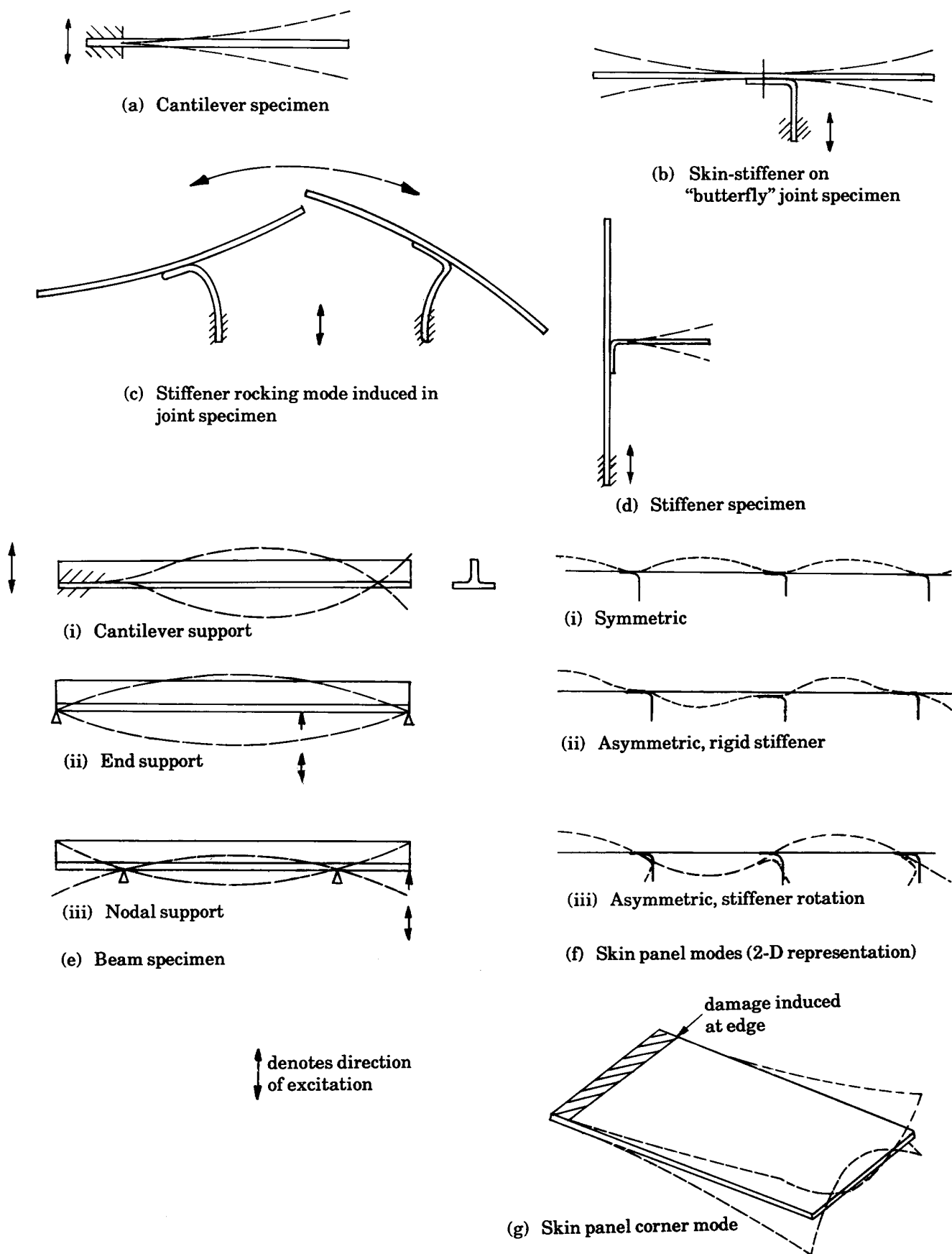
The specimen is usually designed to respond in its first cantilever mode and may be tested as a clamped cantilever or as a 'double cantilever' which is more commonly called a skin-stiffener or 'butterfly' specimen, see Sketches 3.1(a) and (b). A skin-stiffener specimen needs to be designed as nearly symmetric as possible or else a rocking mode may also be induced which may lead to damage in the stiffener portion of the joint, see Sketch 3.1(c).

Indeed the intention of the test may be to provide information on the fatigue performance of the stiffener at the joint location, although the normal procedure would be to excite the specimen in a different plane or use an alternative design, see Sketch 3.1(d). A beam specimen may also be used to provide fatigue data for other locations simulating the response modes of the parent structure. Sketch 3.1(e)(i) shows the usual test layout with the beam excited as a cantilever. However, alternative methods have been used with the beam supported either at its ends or at the nodal points of the selected mode, and the excitation applied via a connecting link to the shaker, see Sketches 3.1(e)(ii) and (iii).

The response of these structural elements in a cantilever mode is generally only a simulation of the stresses produced by the structural panel modes of the parent structure where skin flexure predominates. However, the single mode response theory (*e.g.* that used in Item No. 72005 and other Items in the Sub-series) has been shown to be sufficiently accurate for most engineering purposes. Consequently, the stress distribution in the cantilever mode is assumed to be sufficiently accurate for the determination of the stress to be used to predict the failure, or damage, of the parent structure. Care should be taken in using these data to assess skin damage for modes involving twisting (or rotation) of the stiffeners.

Sketch 3.1(f) shows modes involving stiffener longitudinal flexure and a mode involving stiffener rotation. Although the structural element specimen will only respond symmetrically, as in Sketch 3.1(b), the results obtained for most geometries will also apply to asymmetric modes involving only flexure of the stiffener, as Sketch 3.1(f)(ii). However, stiffener rotation modes can cause damage to the stiffener (rib, frame or other support structure) usually at the attachment to the skin and for such cases the specimen design shown in Sketch 3.1(d) is used.

The bending modes of the structure may also result in damage at the free edge of the stiffener, such as a skin stringer, which is why beam specimens such as those shown in Sketch 3.1(e) are needed. This is especially true for integrally stiffened or monolithic skins where the stringer may be more flexible than for a built-up structure, see Item No. 86025, Section 3.



Sketch 3.1 Response modes of typical test specimen

The specimen itself can also respond in unwanted modes. The intention is for the skin element to vibrate as a cantilever plate, as shown in Sketch 3.1(a) and (b), but the corners of the free edge may also be excited into a panel mode if the respective modal frequency is within the excitation bandwidth, see Sketch 3.1(g). This type of response can lead to damage initiation at the specimen edges that would not be representative of the behaviour of the parent structure. Generally this problem can be minimised by the choice of specimen dimensions although there have been specimens designed to avoid this type of response behaviour, see Section 3.2.2, as well as special specimen clamping arrangements for the same purpose, see Section 3.3.1.

3.2 Geometries for Structural Elements

The main specimen types are described and details of general configurations given in the following Sub-sections. All the configurations shown have been used for random vibration test purposes although the resulting fatigue endurance data may not be available in the open literature. Information is given regarding the potential stress concentration areas and hence the likely damage initiation locations. For composite specimens and some metallic configurations (such as honeycomb) this damage may be confined within the material thickness with no apparent surface defects.

3.2.1 Cantilevers

Clamped Cantilever. This type of specimen is firmly clamped at one end and excited in its first cantilever mode. The fatigue endurance results obtained can be very sensitive to the clamp design which can have a large influence on the failure location, see Section 3.3. However, the clamped cantilever configuration is very useful where damage is anticipated some distance from the clamp edge due to such features as fasteners or section changes. The specimen can be initially designed to exploit these features in order to obtain representative damage.

Plain Specimens. Plain specimens with no structural design features to act as stress concentrations will be most sensitive to the clamping arrangement. Damage is more likely to be non-representative in its location and the actual fatigue endurance obtained may not be realistic unless a clamped joint is used in the parent structure. Plain specimens with geometric shape change in plan view (large root radii) have been used to remove the failure location from the clamp edge. However, failure occurs at the edge of these radii and is dependent on the stress concentration and surface finish of the edge and the results are only applicable to this type of design feature.

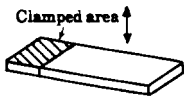
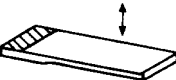
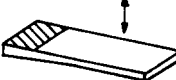
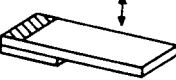
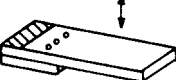
Chemically-Etched Specimens. Metallic specimens with a chemically-etched thickness step have been successfully used with the effect of the clamp kept some distance from the step.

Bonded Joint Specimens. Both metallic and composite specimens have been used with bonded doubler joints to examine the effect of the stress concentration at the thickness step and the peel strength of the bond.

Mechanical Fasteners. Both metallic and composite specimens have been used to investigate the effect of mechanical fasteners through a doubler or attachment flange. These specimens examine the stress concentration at the end of the doubler and they may also be used to examine the effect of bonding used in conjunction with mechanical fasteners.

Configurations of typical cantilever test specimen are shown in the table together with guidance on the potential stress concentration areas.

ESDU Copyright material. For current status contact ESDU.

Type	Joint Attachment	Geometry	Potential Stress Concentration
PLAIN Metallic, Composite	none		near clamp edge
Plain with geometric feature, Metallic, Composite	none		in radius
Chemically etched step, Metallic	none		at step
Tapered thickness composite	none		may be influenced by clamp
BONDED doubler, Metallic, Composite	bonding		at edge of doubler (bonding peel)
MECHANICAL FASTENER Metallic, Composite (with or without bonding)	fasteners (with or without bonding)		at edge of doubler, at fastener head

NOTE: Excitation direction marked ↑

3.2.2 Joints

The skin-stiffener specimen is the most common type of specimen to be used for random vibration endurance. As mentioned in Section 3.1 the specimen generally needs to be designed as symmetrical as possible to prevent a 'rocking' mode causing failure of the stiffener.

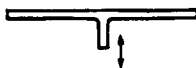
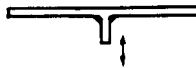
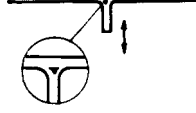
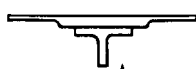
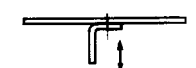
However specimens with a single row of fasteners are usually made symmetric with respect to the fastener row centre-line which means that the stiffener web will not be central, see Sketches 3.1(b) and 3.1(c). Failure of the stiffener does not seem too prevalent for these small offsets although this type of stiffener with a single row attachment can influence the damage location in the skin. In the majority of cases failure occurs in the skin on the side corresponding to the location of the stiffener heel.

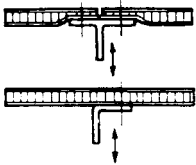
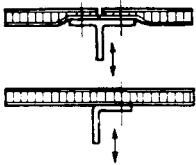
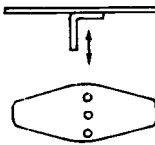
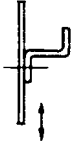
For some applications, the stiffener or rib flange becomes the main item being investigated and an asymmetric specimen usually results (with respect to the direction of excitation), see Sketch 3.1(d). For most specimens the excitation frequency for the stiffener mode will be sufficiently removed from the skin mode to avoid practical problems, although the free skin length could be shortened to raise the skin response frequency.

Other types of joints may also need to be considered such as those occurring in skin panels, stringers (or stiffeners) and frames. Some of these joint types will result in a specimen configuration requiring a different test layout from that described in this sub-section. Often the specimen is tested as a beam with either end or nodal supports, see Sketch 3.1(e)(ii) and (iii).

Many variants of skin-stiffener joints have been used and a selection of configurations are described in the following table together with an indication of the potential damage initiation region. Most specimen damage is in the skin or stiffener material and failure of a mechanical fastener itself appears to be a rare occurrence,

although the fastener can have a large influence on the local damage initiation. Peeling failures of bonded joints appear to be a more commonplace occurrence and failure at a welded joint is almost certain. Jointing compound is often included in the specimen. It will increase the structural damping of the joint and may also affect the region of damage initiation.

Type	Joint Attachment	Geometry	Potential Stress Concentration
PLAIN Metallic, Composite	integrally machined, monolithic		joint radii
Composite	special design		joint radii
Metallic	seam welded		weld line
	superplastically formed and diffusion bonded (SPFDB)		joint radius or skin influenced by any remaining cavity
BONDED Metallic, Composite	plain skin		edge of stiffener flange (bond peel)
Metallic	skin reinforced chemically etched		edge of chemi-etch radius
Composite	skin reinforced tapered skin		(delamination or fibre fracture)
Metallic, Composite	bonded reinforcing		edge of reinforcing, edge of stiffener (bond peel)
MECHANICAL FASTENERS Metallic, Composite	rivets bolts countersunk heads skin dimpling single row fasteners use of jointing compound	 	at fastener head at fastener head, stiffener heel side as above with increased fatigue resistance
MECHANICAL FASTENERS PLUS BONDING	combination of bonded and mechanically fastened	as for mechanical fasteners above	various

Type	Joint Attachment	Geometry	Potential Stress Concentration
WELDED Metallic	spot welds		weld edge
MATERIAL VARIATIONS Metallic: different material specifications	various		as similar metallic specimens
Composite: different material specifications/combinations, lay-ups, manufacturing techniques	various		as similar composite specimens
MATERIAL CONFIGURATIONS e.g. Honeycomb constructions Metallic Composite	mechanical fasteners and/or bonding		at fastener head at fastener head, at panel edge
Structural laminates e.g. ARALL GLARE	mechanical fasteners and/or bonding	 As metallic examples (no chemi-etching)	at fastener head
TAPERED TOP PLATE Metallic Composite (see also text)	most combinations		as above
STIFFENER TEST Metallic, Composite	most combinations		stiffener heel radius

NOTE: Excitation direction marked $\updownarrow$

NOTE 2: A structural laminate is a ply configuration consisting of alternate aluminium and fibre/matrix layers; proprietary examples are ARALL and GLARE which include aramid and glass fibres respectively.

In order to minimise the effects of the skin plate corner modes causing premature damage initiation at the specimen edge, see Sketch 3.1(g), a modified joint configuration has also been employed. This modification involves tapering the plan view of the skin plate and is shown in Item No. 72015 based on tests from Derivations 1 and 5. The original tests used metallic specimens but the modification should also be applicable to composite configurations. It is not certain whether this configuration produces a more consistent or reliable result but it should reduce the plate corner mode problem if the choice of skin dimensions is such as to give close spaced frequencies for skin beam and plate modes.

In order to reduce the overall test duration a relatively high specimen f_n may be useful although a reduction

in cantilever length will also limit the maximum level of stress obtainable. Joint specimens have been tested in their second cantilever mode (for the skin wings) to achieve this aim, Derivation 6. However, a specimen geometry having a skin plate with a higher aspect ratio (L/W) than typical was employed, see Sketch 3.2. A measurement of damping ratio for the second mode of this specimen was approximately double that for the first mode which would indicate that a higher input excitation level is required to obtain a given strain level. Testing in the second mode may also reduce the possibility of skin plate corner modes having an effect at the joint edge.

The choice of a suitable skin stiffener configuration is part of the overall procedure for designing against acoustic fatigue and a knowledge of potential damage initiation features can be very important, see Item No. 86025.

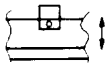
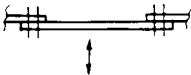
3.2.3 Beams

Structures using integrally stiffened skins, either from metallic configurations (machined or extruded) or composite construction (monolithic), may be prone to damage initiation occurring at the top (free edge) of the stiffener. This can also occur on certain forms of stiffener used on conventional built-up structures. The structural response modes of the skin between ribs or frames can produce high stresses at both the mid-bay of the integral stiffener and near to the rib or frame locations.

Also there is often a shear attachment (cleat) between the stiffener and rib or frame with a fastener providing an additional stress concentration, see mode shapes in Sketch 3.1(f). This additional stress concentration may also be simulated on a beam specimen by adding a fastener in the high stress region.

Certain types of joint, such as a panel lap joint, have also been tested in a beam configuration.

Typical plain beam test specimens are illustrated in the following table.

Type	Joint Attachment	Geometry	Potential Stress Concentration
PLAIN (monolithic) Metallic, composite	none		free edge of stiffener at maximum bending location
Plain with stress concentration	fastener at location of maximum bending		at fastener (as above)
JOINT (panel lap joint) Metallic, Composite	fasteners and/or bonding		at fastener head or tail (and/or bond peel line)

NOTE: Excitation direction marked $\updownarrow$.

3.2.4 Initial damage

It is possible to include initial or artificial damage in the specimen before the start of the vibration test. This is particularly relevant for composite specimens where the effect of BVID (Barely Visible Impact Damage) or a manufacturing defect can be simulated.