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European Aviation Safety Agency

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Research Project:

Evaluation of Strength Degradation of Fabric Particularly Used for Cargo Nets

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Between European Aviation Safety Agency (EASA)

and

Saxon Textile Research Institute at the Chemnitz University of Technology

"Evaluation of strength degradation of fabric particularly used for cargo nets"

Project duration: 10/2008 – 12/2009

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1 Executive Summary

The aim of this study was to investigate the strength degradation of fabric particularly used for air cargo nets. Main focus of the investigation was to compare and evaluate strength degradation of air cargo nets due to their life time and usage.

The project was planned to be executed within 15 months, from October 2008 to December 2009 and was divided into three phases.

Phase 1 Net acquisition
Phase 2 Net testing and analysis
Phase 3 Evaluation and Final report

In Phase 1, a representative number of nets size M (per NAS 3610 – Rev. 10 [1]: 96” x 125”) was purchased including controlled in-service-data. To get a set of representative results, 210 nets of different manufacturers and different in-service-time were tested.

According to planned activities the following ranges had to be considered:
- Nets of 5 different manufacturers
- 2 brand new nets of each manufacturer
- 10 nets with service life time 1 year per manufacturer
- 10 nets with service life time 2 years per manufacturer
- 10 nets with service life time 3 years per manufacturer
- 10 repaired nets with service life time 3 year per manufacturer

It means that 42 nets of each manufacturer should be tested. Some adaptations for the net acquisition and testing were discussed and agreed.

For the net testing in Phase 2 a computer controlled test rig was applied. A test of the complete net is possible at full-scale-size with this test equipment. The advantages of the complete net tests are that all single parts of the nets (lashing lines, reefing hooks, studs, knots) and the interaction of all ropes are considered while testing.

The main results of project are the following:
- A strength degradation up to 50 % was detected, resulting from the ageing processes during the cargo net use including the influence from handling by the operators .
- Most of the tested used nets did not reach the required nominal value according to NAS 3610 Rev. 10.
- Additionally, many of the tested new nets did not reach that required value as well.

The results show the necessity for such an investigation. Even new nets did not always reach the minimum requirement of the NAS 3610 Rev10. Strength degradations up to 50 % within the permitted in-service life time of the nets are an alarming result.

As result of the study, a data base of more than 200 systematically net tests made under full scale tests is now available for the first time world wide. Thus, the study offers a very good base for further decisions concerning testing, certification, rulemaking, approval and standardisation of air cargo nets. First recommendations resulting from test data and their interpretation are presented at the end of this report.

2 Introduction

2.1 Background

Aircraft cargo nets are designed to secure the cargo on air freight pallets and to fix the air freight during periods of in-flight accelerations or survivable crash landing.

The applicable standard NAS 3610 Rev. 10 does require actions to cater for cargo net degradation which are assessed at the time of approval, but specified criteria for activities or measures to be applied are not specified.

At present it is the sole responsibility of the net manufacturer to provide suitable justification to address degradation. This is done by application of safety factor or limitation of life time. Each manufacturer applies own methods of qualification testing as well as means to comply with the degradation requirements. Sufficient data from full scale tests on used nets are not available and no applicable regulation or standard does provide a standardised quality approach.

A survey carried out by EASA showed in most cases compliance with the requirements. In some cases further testing was mandated to provide proper evidence of compliance and in other cases a reduction of life time was required.

In 2006, one part of an independent study was a series of strength tests (full scale test) on used nets. The results were quite alarming because many of used nets didn't reach the required strength as per NAS 3610 Rev. 10. Unfortunately, the variants of nets tested were quite widespread and no reliable statistical data had been received.

2.2 Aims and objectives of the study

The aim of this study was to investigate the strength degradation of fabric particularly used for air cargo nets and to evaluate the received test data for further recommendations respectively potential corrective actions.

Therefore, new nets and used nets with different service life time had to be tested by a full scale test method. The nets should be chosen from at least 5 different manufacturers. In total 210 nets should be tested.

The objectives were to find answers to the following questions:

- Do all new and used nets reach the requirements per NAS 3610 Rev. 10?
- Is strength degradation detectable with the used test method?
- Do differences exist in the results among different manufacturers?
- Are different grades on strength degradation detectable depending on service life time and/or manufacturer?
- Which influences have the repaired sections (areas/parts) within the used nets or the repair itself?

The answers to this question could be used as a technical basis for future aspects of

- Rulemaking
- Certification
- Approval
- Standardisation
- Testing
- Operation
- Maintenance and repair

of air cargo safety nets world wide.

3 Literature review concerning strength degradation of fabrics

3.1 Introduction to strength degradation

Strength degradation is an important subject in field of technical textiles like air cargo nets, geo-synthetics or fabrics for sun protection. At present the important materials are Polyester (PET), Polypropylene (PP), Polyethylene (PE) and in some cases Aramid or Dyneema®. Information about the durability is in most cases available by the manufacturer or in literature, but often a verbal evaluation of durability in "very good", "good" or "bad" is made. The basis of this graduation is often unknown.

The so called "ageing" effect of a polymeric material is a non-reversible change in molecular structure and general properties due to
1) polymer degradation (indirect influences) and
2) product use (direct influences)
Both aspects are important for the overall degradation and especially tensile strength degradation is lowering the product quality decisively. Polymeric molecules are very large on the molecular scale, and their unique and useful properties are mainly a result of their size. Any loss in chain length lowers tensile strength and is a primary cause of structural weakness.

It is also to be noted that different influences affect the durability e.g. ageing of the materials depending on application. Usually, when materials are affected at the same time by several influences it is not clearly identifiable which influence caused the main damage.

Depending on application the following influences are frequently important:
- UV-light
- Temperature / temperature changes
- Rain
- Humidity
- Chemical impact
- Mechanical impact
- Biological impact
- Dust
- Care (cleaning)

Remark:
The four parts UV-light, temperature, rain and humidity most merged under the term "climate" or "weathering".

All these influences itself have a wide range of their physical dimension or can be split up even further:
- UV-light: wavelength
- Temperature: -30°C …… + 50°C
- Rain: yes or no, acid rain
- Humidity: 0 … 100 %
- Chemical impact: what type of chemicals (acid, neutrally, alkaline)
- Mechanical impact: abrasion, snagging, incumbent and imbedded particles …
- …..

This shows the difficulties for the determination of strength degradation and the correct evaluation of data for aging processes. The time of exposure, each single influence (for example weathering) and combination of different influences are complex and difficult to separate.

At present two different methods for the determination of ageing processes were used – natural exposure and artificial weathering.

<u>Natural exposure:</u>
By using the natural exposure, test samples are stored outside for a certain defined time (e.g. in the centre of Europe) and physical parameters (e.g. Climate) are measured during exposure. The exposure time is divided in several parts (e.g. 6, 12, 18, 24 months). At the

end of the exposure the strength degradation is determined by tensile test or other test methods.

Figure 1: Natural exposure area of STFI e.V. – Kap Arkona, Germany

Artificial exposure:
For the artificial weathering special equipment is necessary. This equipment simulates only typical climatic parameters.

Figure 2: UV-Chamber at STFI – simulation of climate

A very extensive overview of possible influences on ageing behaviour is described in [2].

For following discussion of single influences, both, the polymer degradation of used polymer material as well as the direct product use of air cargo nets will be taken into account.

3.2 Influence of time alone

It is to be assumed that also without direct use only during storage the characteristics of man made fibres and textiles are affected by time of storing as indirect influence. Bobeth reported in [3] that over longer storage time changes of the surface of the fibres, discolorations (in meaning of yellowing) and remarkable reducing of tensile strength were detected.

A theoretical explanation for this behaviour of polymeric material is given by Bresee in [4]. All polymeric materials containing at least some non-crystalline material existing at a temperature below the object's glass transition temperature (T_g) will always undergo some physical ageing. The crystalline materials exhibit the greatest changes in properties during physical ageing. Physical ageing occurs universally in the glassy state irrespective of the chemical nature of a polymer. Physical ageing has been seen in a large variety of materials, including fibres.

Since the glass transition temperatures of most fibre-forming polymers are well above room temperature and all fibres contain some non-crystalline areas, **most fibres will exhibit the effects of physical ageing from storage at room temperature. These effects result from the ordering of non-crystalline polymer chains and include decreases in free volume, enthalpy and molecular mobility**.

A fibre that has physically aged can be expected to be harder, denser, and stiffer and to exhibit increasing viscoelastic relaxation times compared to the same fibre that has not been aged physically.

3.3 Influence of UV-light

Since nearly every textile spends at least part of its life exposed to light, contributions of photochemical reactions to textile ageing are common and add significantly to textile deterioration in some cases. A theoretical explanation for this behaviour is also given by Bresee in [4]. The fundamental source of deterioration of chemical or physical properties is chemical changes in polymer composition. In simple terms, chemical changes are those involving destruction and formation of covalent bonds. Unlike physical ageing, which occurs only in non-crystalline areas of polymer materials, **photochemical degradation occurs in both crystalline and non-crystalline areas** since electromagnetic radiation can penetrate both areas. Photochemical degradation will begin at fibre surfaces which are directly exposed to the radiation source and then proceed inward subsequently. This has been shown to be the case in several studies.

Polymer molecular weight changes commonly result from photochemical degradation and substantially change the properties of fibres. The scission of bonds results in a decreased average molecular weight. If a fibre suffers a decrease in molecular weight, a major decrease in tensile strength and elasticity and a moderate decrease in elongation-to-break occurs. In addition to deterioration of these mechanical properties, chain scission results in increased chemical reactivity since new chemical bonds are formed and the degraded material is chemically more diverse. This can be seen in increased sensitivity to chemical reactions such as bleaching, and enhanced sensitivity to subsequent photochemical degradation.

Influences of UV-Radiation is the most frequently treated subject in the technical literature [2, 3, 4, 5, 6, 7] and well-known used test standards for this influence of UV-light are EN 12224, EN ISO 4892-1 and EN ISO 4892-3 [8, 9, 10]. The influence of natural exposure and artificial weathering are usually regarded at the same time.

At the IATA ULDUG-Meeting held on September 2009 in Sydney AmSafe Bridport presented some results about weathering trails on Polyester braids. Here the following could be determined:

- All materials show significant strength loss from weathering.
- Highest losses in dry desert and tropical climates with highest temperatures and UV light intensity.
- Rate of deterioration high at start then reduces in later months.

Test results for fabrics used in air cargo nets concerning degradation caused by UV-light have been investigated in a separate research project of STFI e.V. [11].

3.4 Impact of temperature changes

According to [4] thermal degradation of polymers is molecular deterioration as a result of heating effects. At high temperatures the components of the long chain backbone of the polymer can begin to separate (molecular scission) and react with one another to change the properties of the polymer. Thermal effects can be classified into two general classes. One class involves purely physical structural changes in the fibre substrate whereas the other involves chemical reactions. Since heat may penetrate throughout, structural changes would be expected to occur in both crystalline and non-crystalline areas of fibres.

Melting temperature (T_m) is mostly smaller then Thermal Degradation Temperature. For many fibres, such as the protein and cellulose fibres, the melting point exists at a temperature above which the polymer undergoes thermal decomposition involving chemical changes.

In the following figure the T_m of some polymeric materials is given.

Polymer	Feuchte [%]	T_g [°C]	T_m [°C]
PE		- 125	135
PP		20	170
POM		- 65	178
PET		80	255
PBT		43	223
PA 6	tr 0,2	78	223
	lf 3,0	28	223
	n 8,0	- 8	223
PA 46	tr 0,2	94	287
	lf 3,5	31	287
	n 9,7	- 10	287
PA 66	tr 0,2	90	264
	lf 2,7	39	264
	n 7,2	- 6	264
PA 610	tr 0,1	77	222
	lf 1,5	48	222
	n 3,2	19	222
PA 66/PA6	tr 0,2	81	243
	lf 2,7	29	243
	n 7,4	- 6	243
PA (amorph)	tr 0,3	152	-
	lf 2,9	114	-
	n 5,0	97	-

Figure 3:
Table of T_g and T_m of different Polymers [12] at certain humidity levels [%]

Consequently, although a melting point exists for these polymers, they chemically decompose at temperatures below their T_m's. Therefore, "softening effects" can be seen caused by permanent temperature changes because cross-linking of polymers will be weakened.

Glass transition Temperature	$<$	Crystallisation Temperature	$<$	Melting Temperature	$<$	Thermal Degradation Temperature

The chemical reactions involved in thermal degradation lead to physical and optical property changes relative to the initially specified properties. Thermal degradation generally involves changes to the molecular weight (and molecular weight distribution) of the polymer and typical property changes include reduced ductility and embrittlement, chalking, colour changes, cracking and general reduction in most other physical properties. It can be summarised from [13] that thermal degradation is a thermal decomposition process which is stimulating the physicochemical relaxation of polymers.

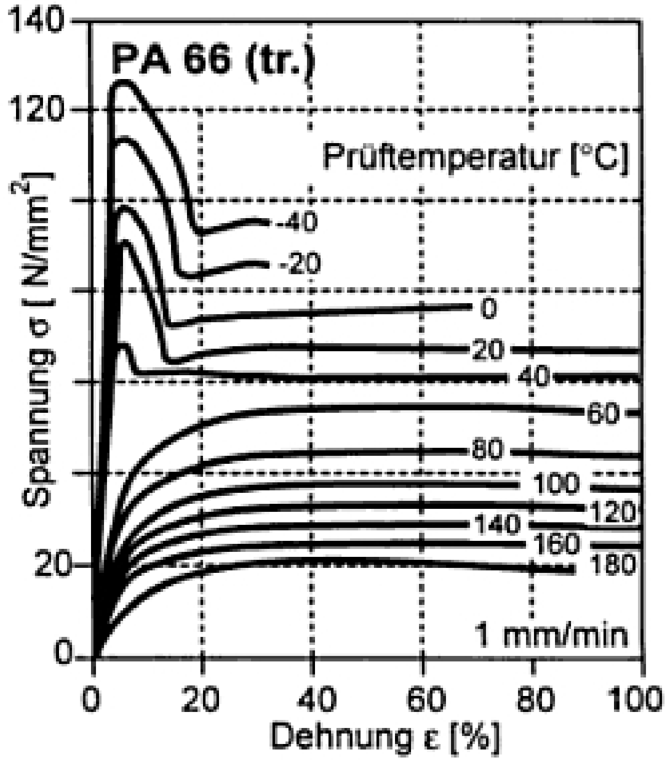


Figure 4:
Stress-Strain-Diagram of Polyamide at different test temperature [12]
(Spannung = tensile strength
Dehnung = strain
Prüftemperatur = testing temperature)

It is well known that strength of textile fibres will decrease with rising temperature, see for example the diagram of stress-strain-diagram with measured values of Polyamid 66 [12].

Furthermore, the temperature has an influence on the structural properties of technical fibres and fabrics as Bobeth describes in [2] that especially by higher temperatures and longer impact times an oxidative and thermal dismantling is possible particular by polyolefin's (polypropylene, polyethylene).

The Research Methods of Thermal Degradation of Polymers are thermo gravimetric Analysis (TGA), differential thermal analysis (DTA) and differential scanning calorimetry (DSC).

TGA refers to the techniques where a sample is heated in a controlled atmosphere at a defined heating rate whilst the samples mass is measured. When a polymer sample degrades, its mass decreases due to the production of gaseous products like carbon monoxide, water vapour and carbon dioxide.
DTA and DSC are analyzing the heating effect of polymer during the physical changes in terms of glass transition, melting, and so on. These techniques measure the heat flow associated with oxidation.

An additional available test standard is the EN ISO 13438: 2004; Geotextiles and geotextile-related products - Screening test method for determining the resistance to oxidation [14].

3.5 Chemical impact

Some fibres are relatively stable to chemical attack according to [4]. For example, some high performance fibres actually are spun from concentrated sulphuric acid and certainly indicate exceptional chemical stability. Other fibres, however, are susceptible to attack by a multitude of chemical species. Reactivity generally increases as the chemical diversity of molecules increases. On this basis, cellulose fibres are less susceptible to chemical attack than protein fibres and polyethylene fibres are even less reactive.
In addition, susceptibility to chemical attack increases as degradation in a fibre increases since the chemical diversity of material more than likely increases as degradation proceeds. Another general rule is that susceptibility to chemical attack increases with decreasing crys-

tallinity. This occurs since chemical species attacking a material can not directly penetrate the dense structure of crystallites. Penetrating the less dense non-crystalline areas is considered much easier. Given enough time, however, crystallites can be destroyed by attack at the crystal surfaces with the destruction then slowly proceeding inward as each crystalline layer is destroyed consecutively. Flax is more resistant to chemical attack than viscose rayon since the latter is significantly less crystalline than the former, even though both are cellulosic.
According to [4] a final rule governing chemical attack is that the rate of chemical reactions generally increases with increasing temperature. Consequently, chemical degradation can be decreased by minimizing temperatures when textiles are exposed to reactive chemical species.

Synthetic polymers are usually well to very well resistant to chemical influences. In a research project [15] different so called “acceleration tests” were made on fibres of polyesters and polypropylene to investigate degradation caused by acids and bases.

Concerning air cargo nets, the chemical impact is mainly to be seen in kerosene and hydraulic fluids contamination but in praxis this impact cannot be clearly identified because it is depending on potential mishandling. Test results for fabrics used in air cargo nets concerning degradation caused by kerosene and hydraulic fluids have been investigated in a separate research project of STFI e.V. [11].

3.6 Mechanical Impact

It is obvious that fibre polymers have a viscoelastic nature. That’s why polymer materials respond to stress on two different time scales. Responses that essentially are instantaneous are called elastic whereas responses that are delayed in time are called viscous. The most fundamental point with regard to the viscous nature of fibres is that their response is time dependent. In other words according to [4], the mechanical response to a stress depends upon the rate of stress.
High mechanical resistance is one of most important parameter of technical textiles. Therefore different high strength polymers are available. One of the most used polymers for high strength applications are special types of polyester. Other materials like Aramid or Dyneema® are also more and more used in special applications.

The maximum mechanical load is usually tested by tensile strength test. It has to be considered that various mechanical influences exist in praxis (tensile, pressure, scrubbing, and abrasion). Also the influence of incumbent and imbedded particles is to be considered.

Test results for fabrics used in air cargo nets concerning degradation caused by mechanical cyclic long-term loading were investigated in a separate research project of STFI e.V. [11]. The two test methods used were an abrasion test and a so called “tumble test” which is similar to crushing and torsion testing.

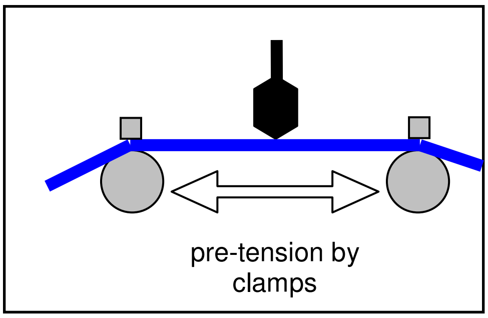


Figure 5: Abrasions test – Schema [11]

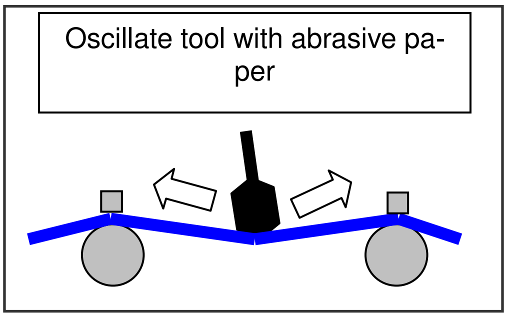


Figure 6: Abrasions test – Function [11]

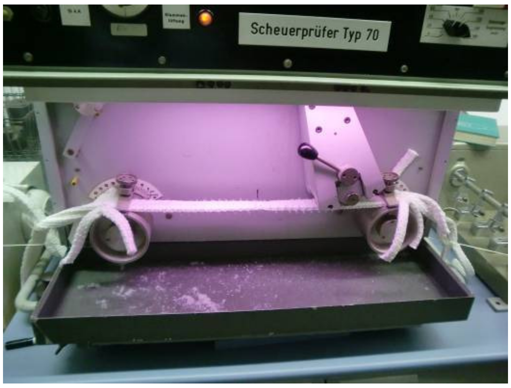


Figure 7: Picture of Abrasions-tester, Type 70 (STFI e.V.) [11]

Figure 8: Crushing and torsion test – basic position (STFI e.V.) [11]

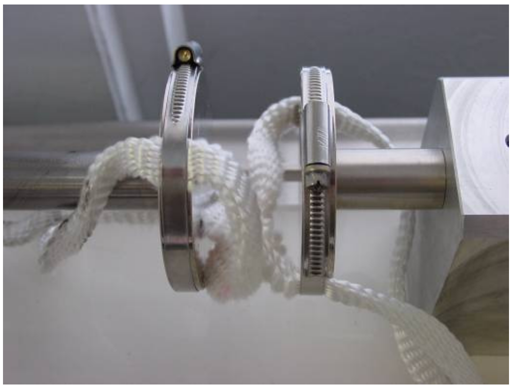


Figure 9: Crushing and torsion test – crushed position (STFI e.V.) [11]

Furthermore, other test standards for pilling, abrasion resistance and various mechanical loads are known and used in textile testing. Well known tests standards which are available for testing of mechanical impacts and could be also applicable to textile fabrics of air cargo nets are:

- EN 388: 2004; Gloves against mechanical risk [16]
- EN ISO 13938-2: 2000; Textiles, bursting properties of fabrics [17]
- EN ISO 13937-2: 2001; Tear properties of fabrics [18]

4 Methodology concerning net strength testing

4.1 Tensile test on ropes (braids)

Classical textile testing to describe stress-strain behaviour of textile structures is done by tensile testing [19, 20]. Tensile testing is carried out on different textile structures, e.g. fibres, yarn, woven and braided ropes and fabrics. Those tensile tests are standardised but differ in testing speed, preload and width of specimen in case of stripe tensile testing.

Some standards for test methods to related products like in this project are available:
- Fibre ropes – Determination of certain physical and mechanical properties [21],
- Load restrains assemblies on road vehicles [22],
- Safety nets – Safety requirements, test methods [23].

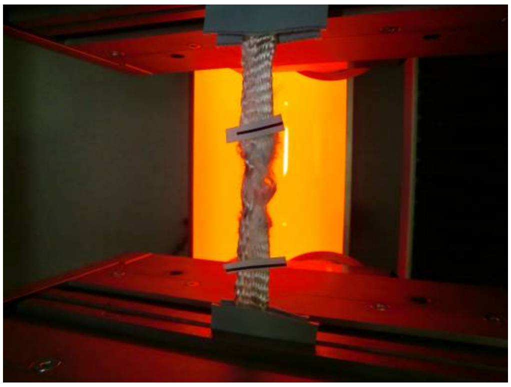


Figure 10: Tensile test on rope for air cargo nets – test specimen after rupture

Figure 10 shows the tensile test on a rope for air cargo nets after rupture. Here specific hydraulic clamps and a direct elongation measurement system (see bench marks) were used. The results of this test are the maximum tensile force at time of rupture and the associated elongation. Additional parameters can be defined and measured, e.g. elongation measurement at predefined force or force measurement at predefined elongation value.

4.2 Other known net test procedures

In the applicable standard NAS3610 Rev. 10 [1] requirements for Cargo Nets are described, but the criteria for test activities or measurements to be applied are not specified.

A quite common procedure for the determination of the performance of new or used nets at present is the “crane method “. Here concrete blocks up to a specified load are stacked on a pallet. In this particular test the 10% COG offset can be applied accordingly. A welded steel frame structure resembling the outer dimensions of the expanded net is placed on the loaded pallet. The net would be pulled over the steel structure and appropriately fixed to the pallet attachment points. The steel structure would then be lifted off the ground by means of a crane. A calibrated load transducer provided between crane and steel structure is used to confirm that the net is loaded as required.
The test would be considered as passed, if within a period of greater than 3 seconds no net rupture occurs after the pallet is lifted off the ground.

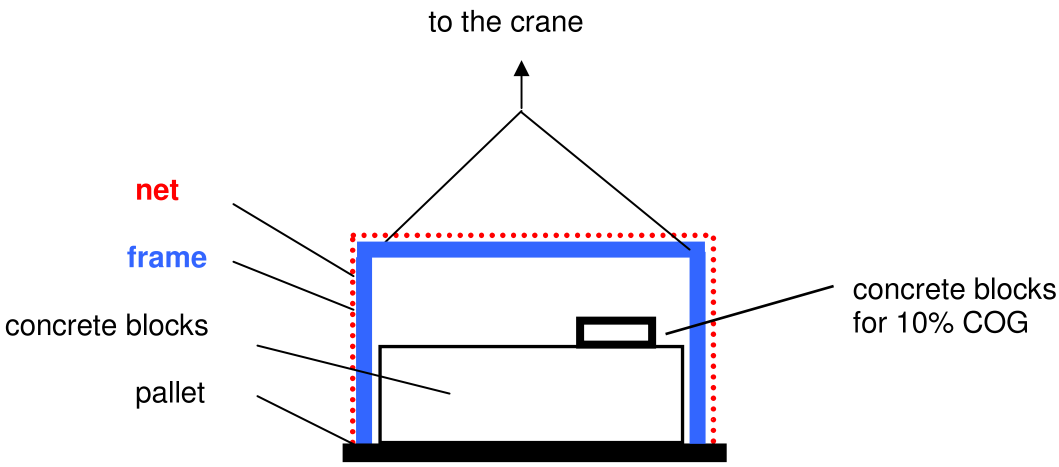


Figure 11: Full scale test set-up – crane method

With this method the net is supported on all edges and fixed in an idealized shape by a compact steel frame during testing.
Today many different variants of above test set-up are used by industry.

4.3 Test methodology developed by STFI

As described above a sufficiently standardized approach (e.g. DIN, EN or an ISO standard) to address maximum (ultimate) load testing of cargo nets does not exist for this highly sensitive area.

Therefore, STFI developed a net testing method and equipment (see figure 12) to test the complete net according to STFI internal test procedure [24] at full scale test.

Advantages of this full scale test set-up are that all single parts of the net and the interaction of all ropes (braids) will be considered while testing. Also the influence of corner cords (lashing lines) and reefing hooks for shortening have to be considered. The STFI test method does address another essential issue, the interface net to pallet. For attaching the net to the pallet proper fastening elements (double studs) are used to achieve representative load transfer between net and pallet.

Figure 12: Test set-up for air cargo nets (size 96"x125"x118") at STFI e.V., (full scale test)

The main parameters of the test set-up device are:

Testing force:	maximum 240 kN
Testing (lift) length:	3500 mm
Testing velocity:	up to 200 mm/min
Dimension of test sample:	A) 2 x 2 m up to 5 x 5 m (stretched plane)
	B) 96" x 125" x 64/96/118" (air cargo safety nets)

Special equipment:

- Software controlled construction variable in velocity, length and force.
- Free programmability of testing routines (cycles, exposure time, etc.).
- Different design of load-rack according to application possible.
- Adaptation to various sizes of test samples

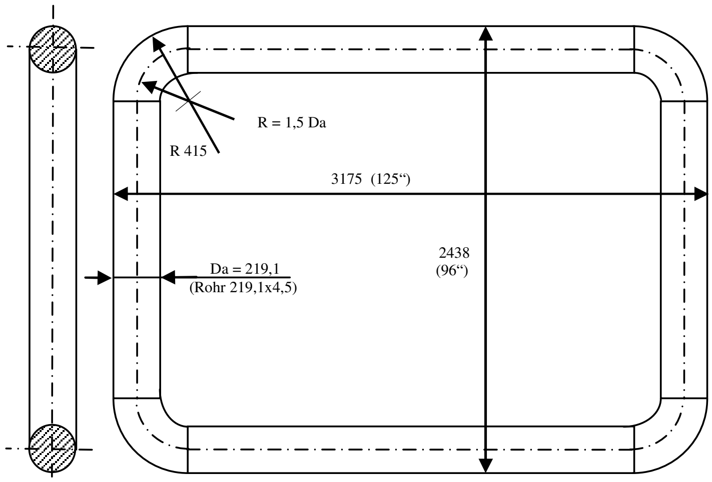


Figure 13: Tubular steel frame for testing air cargo safety nets

Further advantages of this test equipment are:

- The net is not supported over its complete outer shape by a fixed frame. Inadmissible frictional forces particularly at the corners could be excluded this way.

- The nets can be tested (loaded) with a defined test speed.

- The reached forces over the entire phase of the test are accurately recorded up to the point of net rupture.

- The reached elongation over the entire phase of the test is accurately recorded up to the point of net rupture.

- A net with a height of 118" can be reefed (shortened) by several meshes.

5 Implementation of Evaluation of strength degradation of fabric particularly used for cargo nets

5.1 Management, Administration and Time Schedule

5.1.1 Project Structure

Two main parties were involved in the project. EASA did initiate and lead the project and STFI e.V. did carried out the work as subcontractor. STFI is an independent private non-profit research institute.

5.1.2 Project Monitoring and time schedule

The project duration was planned to be from October 2008 to December 2009. The complete work load was carried out in 8 work packages as shown in annex 1.

5.1.3 Project Management Changes

No changes had been requested by any of the participants during the project.

5.2 Net acquisition

5.2.1 Technical aspects of acquisition (Number of nets & time window)

The primary objective of the project was a systematic investigation of strength degradation of fabric particularly used for cargo nets. Therefore brand new nets and nets with different service life time (1 year, 2 years, 3 years, 3 years and repaired) should be tested. Tensile full-scale tests were done at STFI on the test set-up as described above.

To get a set of representative data the study should include nets of 5 different net manufacturers (at least one non European). The net samples should be taken from operational service of 5 different airlines including at least one cargo airline.

Nets to be tested:
- 2 brand new nets/manufacturer
- 10 nets with 1 year service life time/manufacturer
- 10 nets with 2 year service life time/manufacturer
- 10 nets with 3 year service life time/manufacturer
- 10 repaired nets with 3 year service life time/ manufacturer

This means 210 net tests have to be tested with anonymous marking of the nets.

The age of nets (service life time) was defined as from date of manufacturing (month/year) up to the date of arrival at STFI e.V. (month/year).

Service life time	Date of manufacturing up to test date
1 year	8 – 16 month
2 years	20 – 28 month
3 years	32 – 40 month

Figure 14: Groups of service life time

5.2.2 Summary of contacted Resources/Organisations

Net acquisition did prove to be difficult because most of the contacts had to be newly established. Procedure of net acquisition was done and controlled by following steps:

1. Establishment of personal contacts (via e-mail, phone and direct visits)
2. Status request for available nets (manufacturer, service life, etc.)
3. Status request for collected nets (regular with different feedbacks)

4. Coordination of net delivery and invoicing

Some problems occurred on the way of net acquisition and were solved by discussions and further clarifications with EASA. Many concerns of airlines had to be discussed in detail and in some cases additional confidential agreements were made. The most frequent questions about getting test results, test witnessing and justifications of test method could be clarified sufficiently.
However, out of the high number of organisations which were contacted only about one third did respond.
It was easier as expected to get in touch with the American air cargo business but mostly because of close European contact persons who supported this investigation.

5.2.3 Summary of supporting Resources/Organisations

Beside all European contacts, for the consideration of non-European net manufacturer, it was possible to establish contacts to 12 non-European airlines and to one non-European repair station. In total with more than 200 acquired nets, 6 out of 7 net manufacturers world wide could be covered concerning used air cargo nets.
However, in most cases a maximum of two airlines per net manufacturer could be covered.

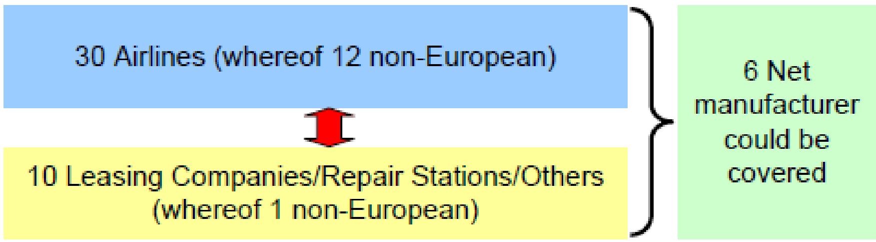


Figure 15: Net acquisition – contacts

In total 243 nets were collected for testing which are divided into following amounts:

- brand new ones : 42 pieces of 7 manufacturers
- 1 year service life time: 64 pieces of 7 manufacturers
- 2 years service life time: 61 pieces of 7 manufacturers
- 3 years service life time: 52 pieces of 5 manufacturers
- without DOM: 11 pieces of 2 manufacturers
- > 3 years old: 7 pieces of 2 manufacturers
- wrong net size: 6 pieces of 1 manufacturer

5.2.4 Changes in net acquisition

During the net acquisition it became obvious that it was very difficult to get the desired numbers of nets per manufacturer. Therefore, the following change of net acquisition was decided between EASA and STFI in a first progress meeting.

- Brand new nets: 5 pieces of 6 manufacturers
- 1 year service life time: 10 pieces of 6 manufacturers
- 2 years service life time: 10 pieces of 6 manufacturers
- 3 years service life time: 10 pieces of 6 manufacturers

Another reason for above change was the fact that nearly all used nets were repaired. So the category "Repaired nets with 3 year service life time / manufacturer" could be deleted.

Due to non-availability of used nets with 3 years service life time of two net manufactures, a further change of net testing was agreed between EASA and STFI in a second progress review meeting.

The investigations of the influence of the number of reefing hooks was agreed with proceeding the testing of nets from existing overhangs of other manufacturer's.

210 nets had to be tested to fulfil the contract which was completed on 12.11.2009.

5.2.5 Net marking (anonymous)

The sources of the nets and the test results were treated anonymously for a later public version of the final report. That means before testing all nets had been marked with a special code.

The following description explains the used system for anonymisation of the cargo nets within this investigation. The codes given in this report should enable the reader to compare the results of new nets of each manufacturer with the results of used nets over net service life time without actually revealing the name of the manufacturer.

The coding for the anonymised test nets consists of 5 positions:

1. Pos.	Code for manufacturer	letter
2. Pos.	Service life time of the net (years)	number
3. Pos.	Airline	number
4. Pos.	remark (flexible) to the conditions of net	new – new net R – „repaired“ net
5. Pos.	serial-number of net in a test series	01 – first net of test series 02 – second net of test series

For example:

Code	Position 1	Position 2	Position 3	Position 4	Position 5
	Manufacturer	Service life time	Airline	Remark	serial-number of net in a test series
A-0-11-new-01	A	0	11	New	01
B-2-11-R-02	B	2	11	R	02
C-3-11-R-03	C	3	11	R	03

Figure 16: Example of net codes

With help of the internal documentation, the source of each net is traceable.

1. Position: Code for manufacturer

The coding for the net manufacturers is confidentially deposited in the STFI.

2. Position: Service life time of the net (years)

The starting date of calculating the service life is the date of manufacturing indicated on the name plate by each manufacturer. Information about when the net did really start its service life after manufacturing is not available. The time between date of manufacturing and start of service life of each net cannot be used for further investigation.
Because the time needed for both, net acquisition and time of testing itself did involve some months, the time of "net service life" could potentially slip with the ongoing investigation and

thus had to be clearly identified. Therefore the „time windows” described in 5.2.1 were created.

3. Position: Airline

The third position of the net coding considers the airline where the net was used. Is the airline unknown a question mark „?“ is used. The list of the airlines is confidentially deposited in the STFI.

4. Position: Remark

The fourth position describes the condition of the net. It shows, if the net is a new net or a used / repaired one.

5. Position: serial-number of net in a test series

The fifth position shows the serial-number of net in a test series. A net series means a group of nets of the same manufacturer and the same age. Such a net series can be used e.g. for statistical analysis.

5.3 Net testing

5.3.1 Net size and load conditions

The nets to be tested in the project are specified in the NAS 3610 Rev. 10 as size code “2M2”. The nominal dimension of the nets with size code “2M2” is 96” x 125”.

For these net sizes the following requirements are described in the NAS 3610 Rev. 10.

Load condition 32: 38.000 lbs = 169.000 [N] in upward direction without failure for at least 3 seconds

For consideration of the offset of 10 % centre of gravity in a further step a load condition of 186.010 [N] (+ 10 %) was established, as the 10% offset could not be realised with the test stand.

5.3.2 Agreed test sequence

To use the following test sequence for all nets was confirmed by EASA.

Pos. Test sequence

(01) Preload of 50.000 N with following load relaxation.
(02) Automatic test up to a load of **169.100** [N], load condition 32 = 38.000 lbs (NAS 3610) and holding for **3,5** seconds with following load relaxation.
(03) Automatic test up to a load of **186.010** [N] – Safety factor 10% (for 10% load displacement out of centre of gravity) and holding it for **3,5** seconds and following load relaxation.
(04) Automatic test up to breaking load. (Determination of maximum breaking load [N].)

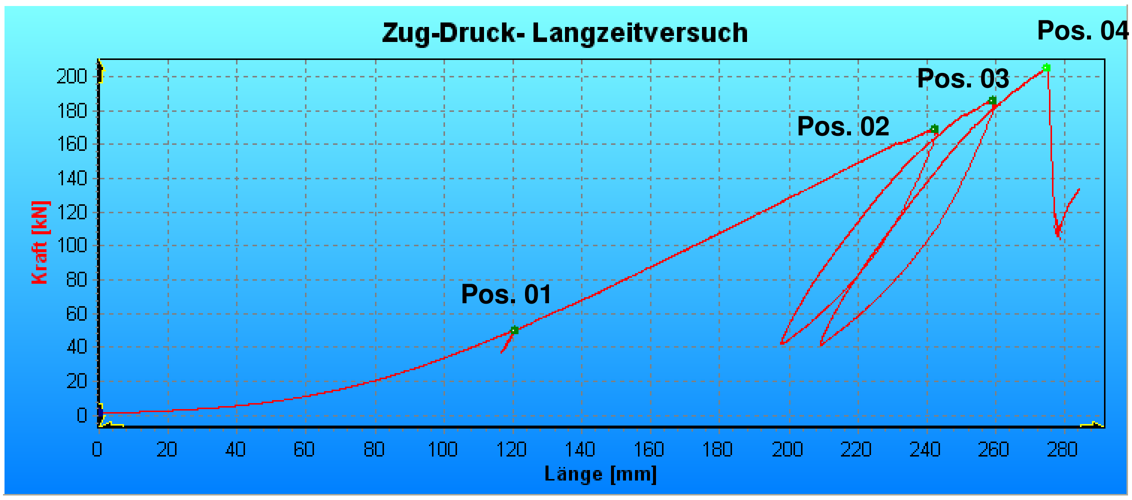


Figure 17: Net test – typical diagram F = f (l)
(Zug-Druck-Langzeitversuch = tensile test
Kraft = load, Länge = length)

5.3.3 Evaluation of test data (calculation)

All results are documented in printed test reports and saved as a data file. The evaluation of data, separated according to manufacturer, is done in the following form.

a) Deviation of load of the used net to the nominal value 1 = 169,1 [kN]

$$D_{nom} = \frac{F_U - 169{,}1}{169{,}1} * 100\%$$

with: D_{nom} [%] – deviation to the nominal value 1 = 169,1 [kN]
F_U - max. breaking load of used net [kN]

b) Deviation of load of the used net to the mean value of new nets [%]

$$D_{comp} = \frac{F_U - F_{mean}}{F_{mean}} * 100\%$$

with: D_{comp} [%] – deviation to mean value of the new net
F_U - max. breaking load of used net [N]
F_{mean} – mean value the new net

Remark: Comparison only done for nets with the same part-number.

5.3.4 Overview of tests carried out

The following table show the tests carried out.

Code	Net age in years	No. of tested nets
A	New	5
	1	10
	2	10
	3	10
B	New	5
	1	10
	2	10
	3	10
C	New	5
	1	10
	2	2
	3	0
D	New	5
	1	6
	2	10
	3	0
F	New	5
	1	10
	2	10
	3	10
G	New	5
	1	10
	2	10
	3	10
H	-	32
	in total	210

Figure 18: Tested nets – overview

During the net acquisition it became clear that it will be very difficult to get the desired numbers of nets per manufacturer.

It was agreed to test nets from existing overhangs of other manufacturer's in a special category H. So the investigations for the influence of the number of hooks for reefing was agreed additionally to fulfil the number of 210 tests.

6 Analysis and Results of net tests

6.1 Overview all nets

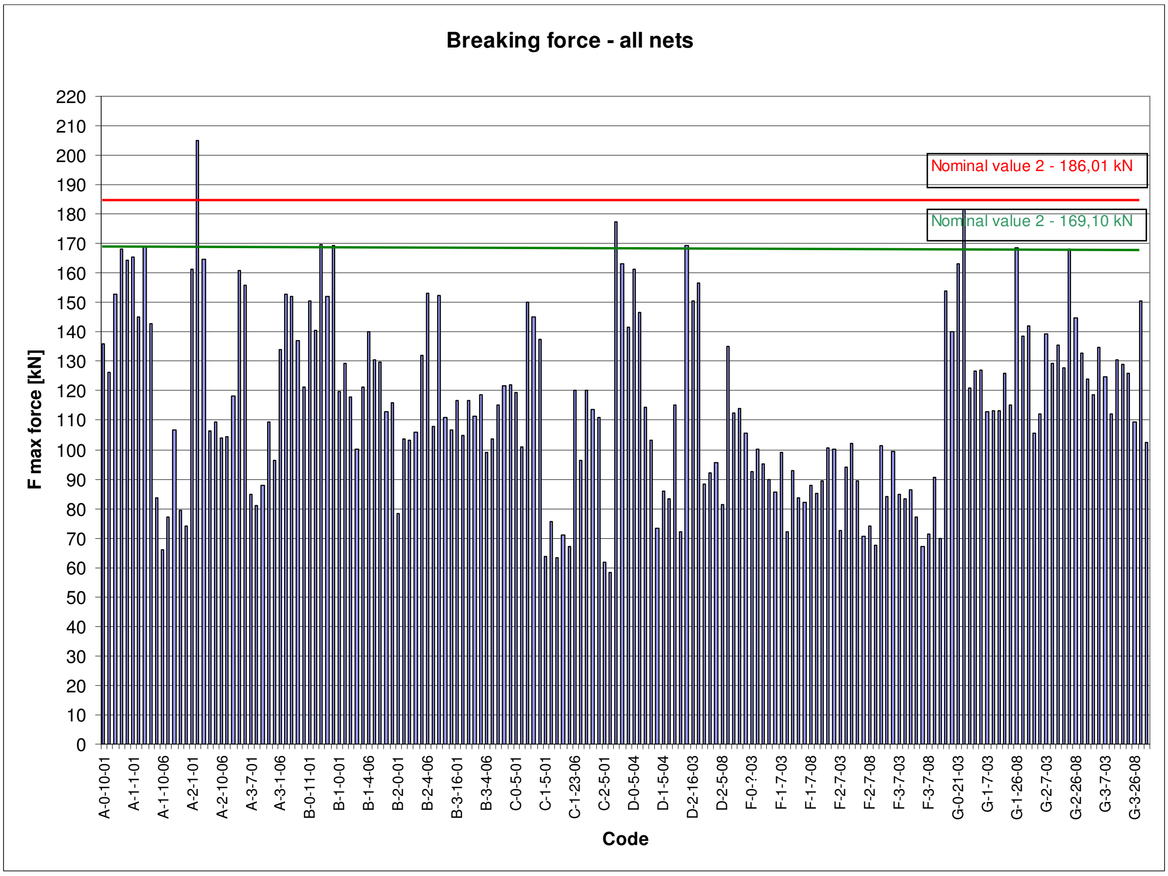


Figure 19: Diagram – Breaking force – all nets

Figure 19 gives a very rough overview of the test results of the tested nets. The next chapter will provide a more specific overview. Out of 180 considered nets only 12 reached the nominal value 1 = 169,1 [kN]. It means only 6,7 % of the tested nets fulfil the NAS 3610 Rev. 10. An overview of all results of the tested nets is shown annex 2. Here all single values and mean values per manufacturer are listed.

For a correct assessment of all test results the following aspects have to be considered:
- The results reflect nets of 6 different manufacturers / net constructions.
- The tested nets differ in their service life time (new, 1, 2 or 3 years)

Also important are the differences between the manufacturers and the design differences between nets of the same manufacturer. For some manufacturers nets there are many variations concerning net design for the size 2M2 (e.g. heavy duty, standard, light weight). This could mean a number of different part numbers which were included in the same certification approval (ETSO/JTSO) for a given manufacturer.

Hence the nets can differ by:
- weight
- types of reefing hooks
- number of reefing hooks
- lashing line / zipper system
- type of ropes (woven/braided)
- net construction (knotted / knotless)

It is clear that those differences would have an influence on the test results for full scale net testing. Each element of the net has to be in a condition that the whole net can fulfil the requirements.
Figure 20 shows the mean values of the reached maximum load of the tested net per manufacturer, the deviation of the reached values to the nominal value and the deviation of used nets to the mean value of the new nets.

Manu-facturer	Age year(s)	mean value [kN]	D_{nom} - Deviation [%] to the nominal value1 = 169,1 [kN]	D_{comp} Deviation [%] to the mean value of the new net
A	new	138,4	-18,2	
		166,3	-1,7	
	1	155,7	-7,9	new nets had different P/Ns
		81,2	-52,0	-41,3
	2	167,7	-0,8	new nets had different P/Ns
		108,4	-35,9	-34,8
	3	92,0	-45,6	-33,5
		144,1	-14,8	new nets had different P/Ns
		121,3	-28,3	-27,1
B	new	150,4	-11,1	
		158,0	-6,6	
	1	121,9	-27,9	new nets had different P/Ns
		100,3	-40,7	new nets had different P/Ns
		125,9	-25,5	new nets had different P/Ns
	2	91,0	-46,2	new nets had different P/Ns
		103,3	-38,9	new nets had different P/Ns
		118,9	-29,7	new nets had different P/Ns
		124,3	-26,5	new nets had different P/Ns
		110,9	-34,4	new nets had different P/Ns
	3	110,8	-34,5	new nets had different P/Ns
		116,8	-30,9	new nets had different P/Ns
		111,3	-34,2	new nets had different P/Ns
		109,2	-35,4	new nets had different P/Ns
		121,7	-28,0	new nets had different P/Ns
		122,1	-27,8	-22,7
C	new	130,7	-22,7	
	1	68,1	-59,7	-47,9
		112,2	-33,6	new net had different P/N
	2	60,3	-64,3	-53,9
D	new	170,2	0,7	
		149,7	-11,5	
	1	92,0	-45,6	-38,5
		115,0	-32,0	-32,4
	2	72,1	-57,4	-57,6
		144,9	-14,3	new nets had different P/Ns
		89,4	-47,1	-40,3

Manufac-turer	Age year(s)	mean value [kN]	D $_{nom}$ - Deviation [%] to the nominal value1 = 169,1 [kN]	D $_{comp}$ Deviation [%] to the mean value of the new net
F	new	101,5	-40,0	
	1	86,8	-48,7	-14,5
	2	87,3	-48,4	-14,0
	3	81,4	-51,9	-19,8
G	new	147,1	-13,0	
		155,2	-8,2	
	1	119,8	-29,2	-22,8
		141,1	-16,6	-4,1
	2	124,3	-26,5	-19,9
		139,5	-17,5	-5,2
	3	124,1	-26,6	-20,0
		123,5	-27,0	-16,0

Figure 20: Mean values and deviations of mean value to nominal value and for comparison mean value new nets to mean value used nets

6.2 Results depending on age of the nets

The category of different service life time of the nets was chosen to see the influence of the age of the net (new, 1 year, 2 years, 3 years). Each net is labelled with the date of manufacturer (DOM). For this project the service life time of a net was defined as from DOM up to storage in STFI. But it happened that e.g. a 1 year old net did appear to be more used than a 3 years old net (see figures 21, 22).

Figure 21: Net 3 years old

Figure 22: Net 1 year old

Hence it may be possible that a net was stored for a long time period and may have been in service only 10 times before it was sent to STFI. The definition concerning the age of the net was described in chapter 5.2.1. An overview of the age of the nets and failure modes are shown in Annex 3.

6.2.1 Results new nets

Only the results of new nets for a given manufacturer could be considered suitable for a direct comparison of the different aged nets of the same manufacturer, because the different and very high influences of the ageing processes will shift the results in different directions.
Thus a batch of new nets had been tested for each manufacturer to have a baseline for an assessment of degradation.

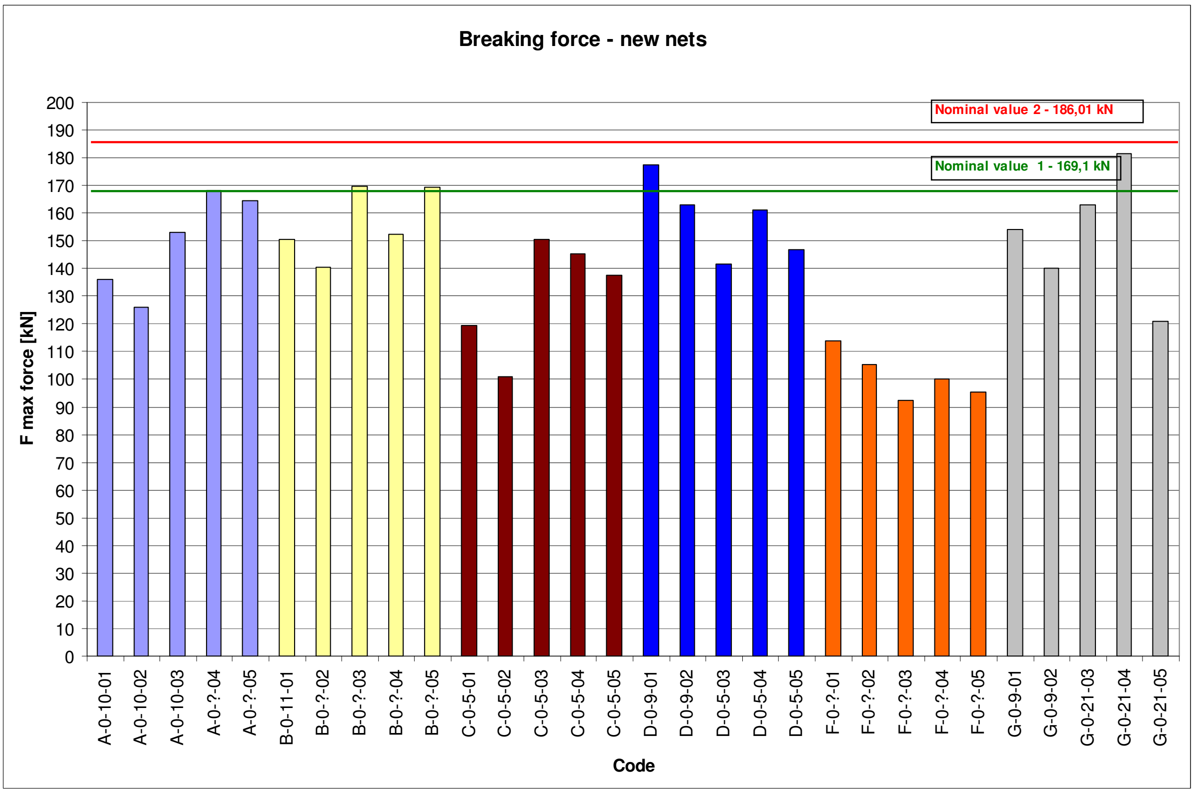


Figure 23: Test results of the new nets

Only 4 of 30 nets reached the nominal value 1 = 169,1 [kN] and no net reached the nominal value 2 = 186,01 [kN] (Safety factor 10% - for 10% load displacement out of centre of gravity).
The deviations of the mean value to the nominal value differ up to 43,7 %.

Manufacturer	Load mean value [kN]	appr. mass of net [kg]	number of all hooks	type of rope	construction
A	**138,4**	14,35	18	**braided**	knotless
	166,3	14,00	18	**woven**	knotted
B	150,4	17,94	18	braided	knotless
	158,0	17,63	18	braided	knotless
C	130,7	12,15	18	woven	knotless
D	**170,2**	15,43	**24**	woven	knotted
	149,7	14,17	**18**	woven	knotless
F	101,5	14,09	18	woven	knotted
G	147,1	14,23	20	woven	knotted
	155,2	19,38	20	woven	knotted

Figure 24: Test results of the new nets - details of net construction

Figure 24 shows clearly that there is a connection between the maximum load and:

- the weight of the net
- number of reefing hooks and
- assumedly the type of rope/construction.

A connection between the load and the type of rope (woven/braided) can be assumed for manufacturer A. The results show different loads (by the same weight, number of hooks) for different types of ropes.

The results of manufacturer D show a clear influence from the number of hooks.

6.2.2 Results of 1 year old nets

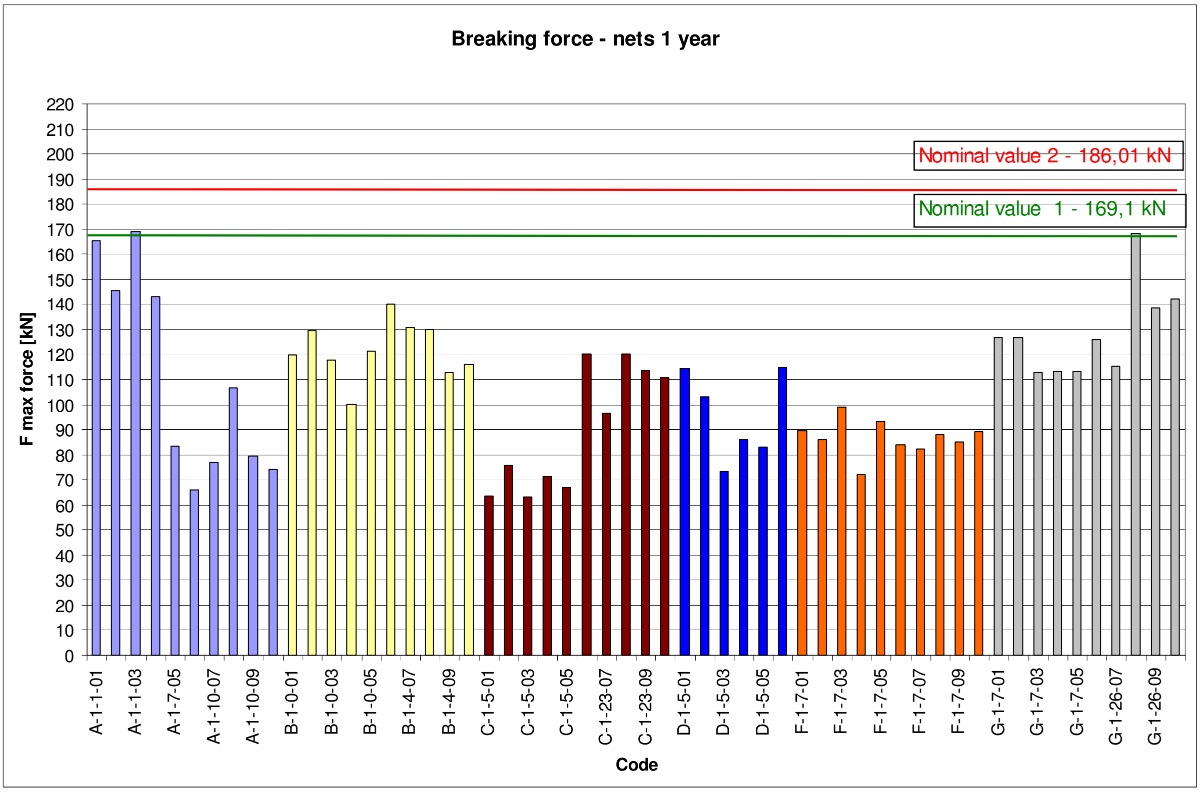


Figure 25: Test results of the 1 year old nets

Only 1of 56 nets reached the nominal value 1 = 169,1 [kN] and no net the nominal value 2 = 186,01 [kN] (Safety factor 10% - for 10% load displacement out of centre of gravity).
The deviations of the mean value to the nominal value differ up to 62,6 %.

6.2.3 Results of 2 years old nets

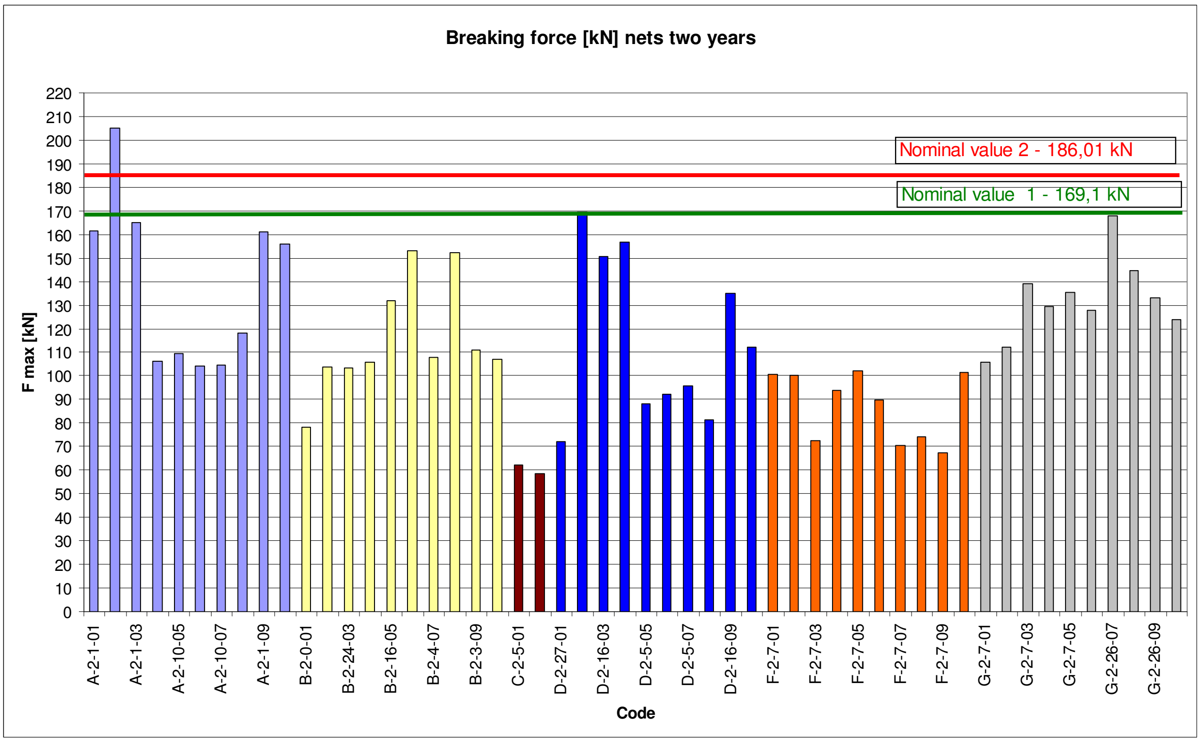


Figure 26: Test results of the 2 years old nets

Only 2 of 50 nets reached the nominal value 1 = 169,1 [kN] and only 1 net reached the nominal value 2 = 186,01 [kN] (Safety factor 10% - for 10% load displacement out of centre of gravity).
The deviations of the mean value to the nominal value differ up to 62,6 %.

6.2.4 Results of 3 years old nets

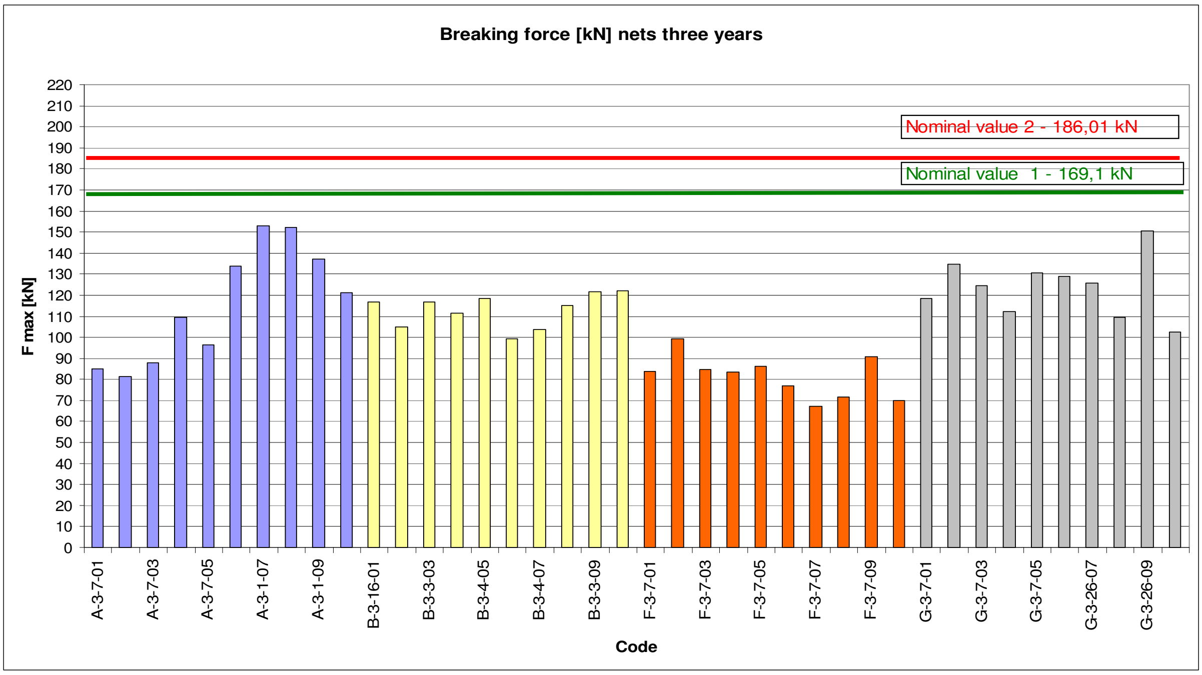


Figure 27: Test results of the 3 years old nets

No net of the 40 tested reached the nominal value 1 = 169,1 [kN]. The deviations of the mean value to the nominal value differ up to 60,4 %.

6.3 Results depending on manufacturer of the nets

6.3.1 Manufacturer A

All planned nets of each category of manufacturer A could be tested. It means:

- new nets 5 pieces
- 1 year old 10 pieces
- 2 years old 10 pieces
- 3 years old 10 pieces

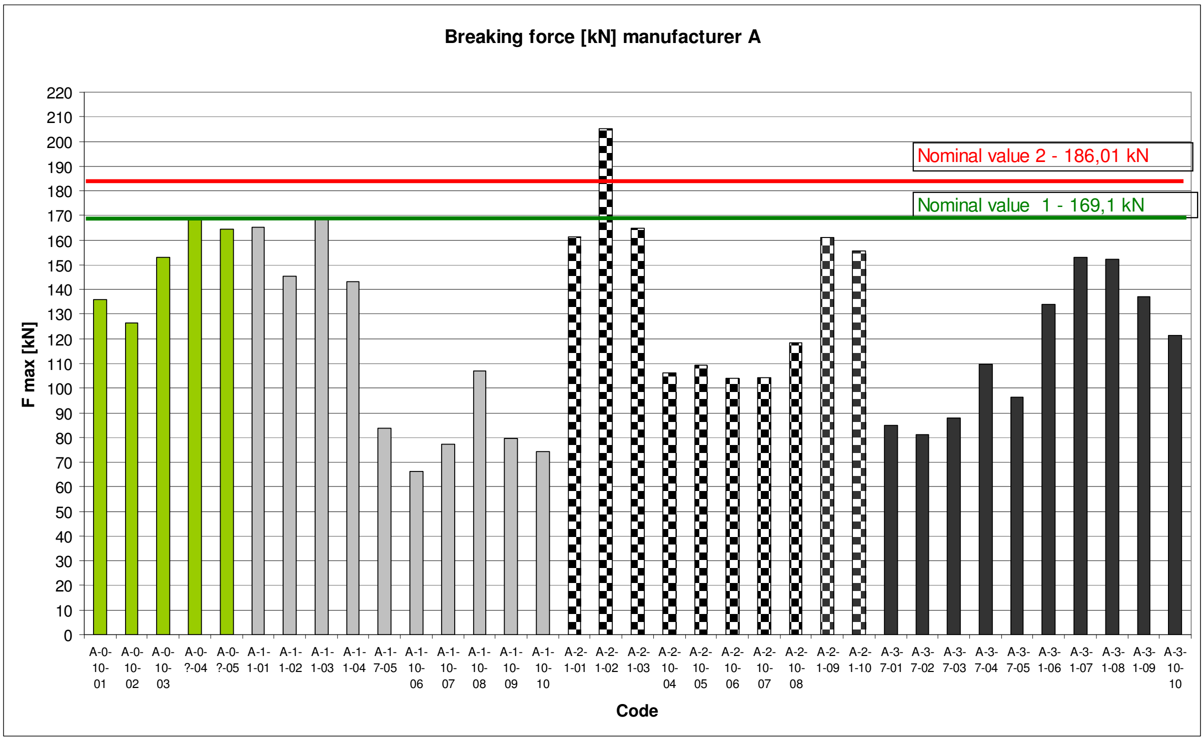


Figure 28: Test results of manufacturer A

The results of manufacturer A are very different. A reason for that is that different P/Ns were tested with different weight of the nets because 3 different part numbers (net variants) had been tested within this group. The nets with the highest weight reached the best load in all categories (new, 1, 2, and 3 years).

6.3.2 Manufacturer B

All planned nets of each category of manufacturer B could be tested. It means:

- new nets 5 pieces
- 1 year old 10 pieces
- 2 years old 10 pieces
- 3 years old 10 pieces

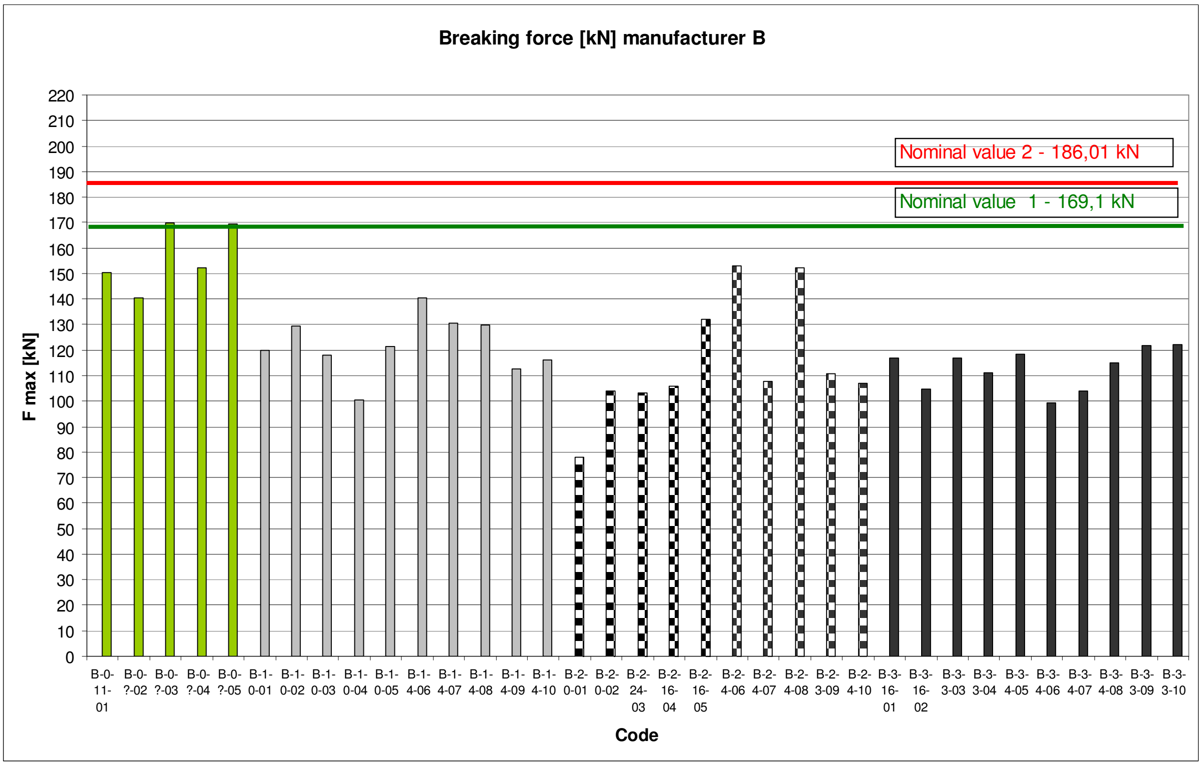


Figure 29: Test results of manufacturer B

The nets of manufacturer B are mostly with the highest weight. The results could be better if other (and more) hooks were used (see category H). Often the failure mode was hook rupture or net break near at hook.

6.3.3 Manufacturer C

Not all planned nets of each category of manufacturer C could be tested. It means:

- new nets 5 pieces
- 1 year old 10 pieces
- 2 years old 2 pieces
- 3 years old nets not available

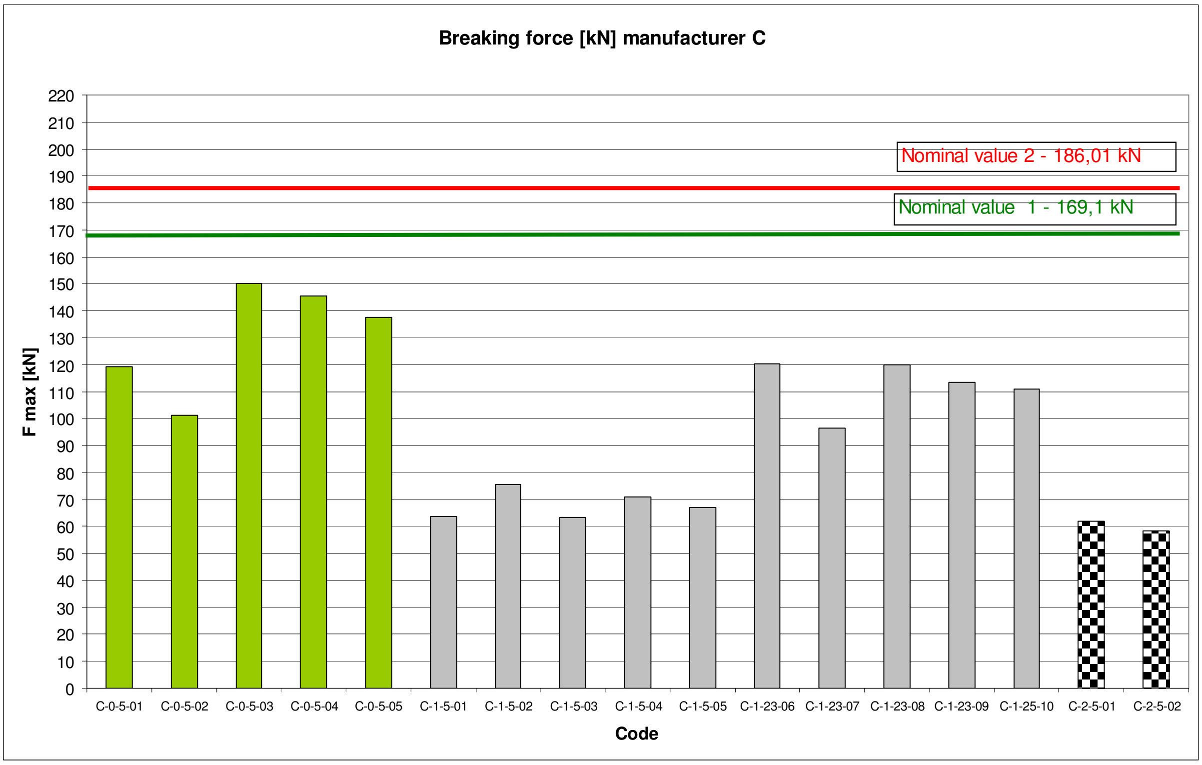


Figure 30: Test results of manufacturer C

All tested nets of manufacturer C had a weight lower than 13 kg. These nets are the lightest of all nets tested in this research project. The influence of the number of hooks is to be seen in category 1 year (gray). The first 5 specimens are a net variant provided with 18 hooks and specimens 06 to 10 are another net variant provided with 24 (by nearly same weight).

6.3.4 Manufacturer D

Not all planned nets of each category of manufacturer D could be tested. It means:

- new nets 5 pieces
- 1 year old 6 pieces
- 2 years old 10 pieces
- 3 years old nets not available

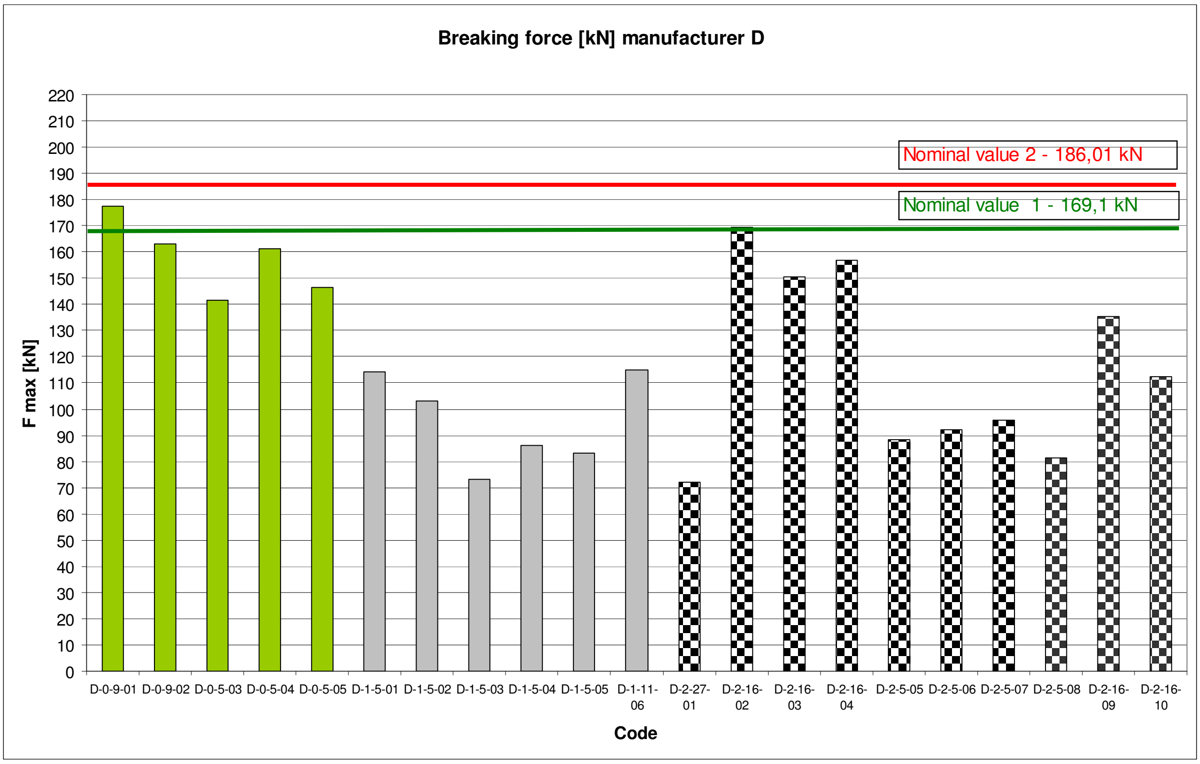


Figure 31: Test results of manufacturer D

Also for manufacturer D the net variant with the highest weight and 24 hooks reached the highest load (new nets specimen 01, 02 and 2 years old nets specimen 02, 03, 04).

6.3.5 Manufacturer F

All planned nets of each category of manufacturer F could be tested. It means:

- new nets 5 pieces
- 1 year old 10 pieces
- 2 years old 10 pieces
- 3 years old 10 pieces

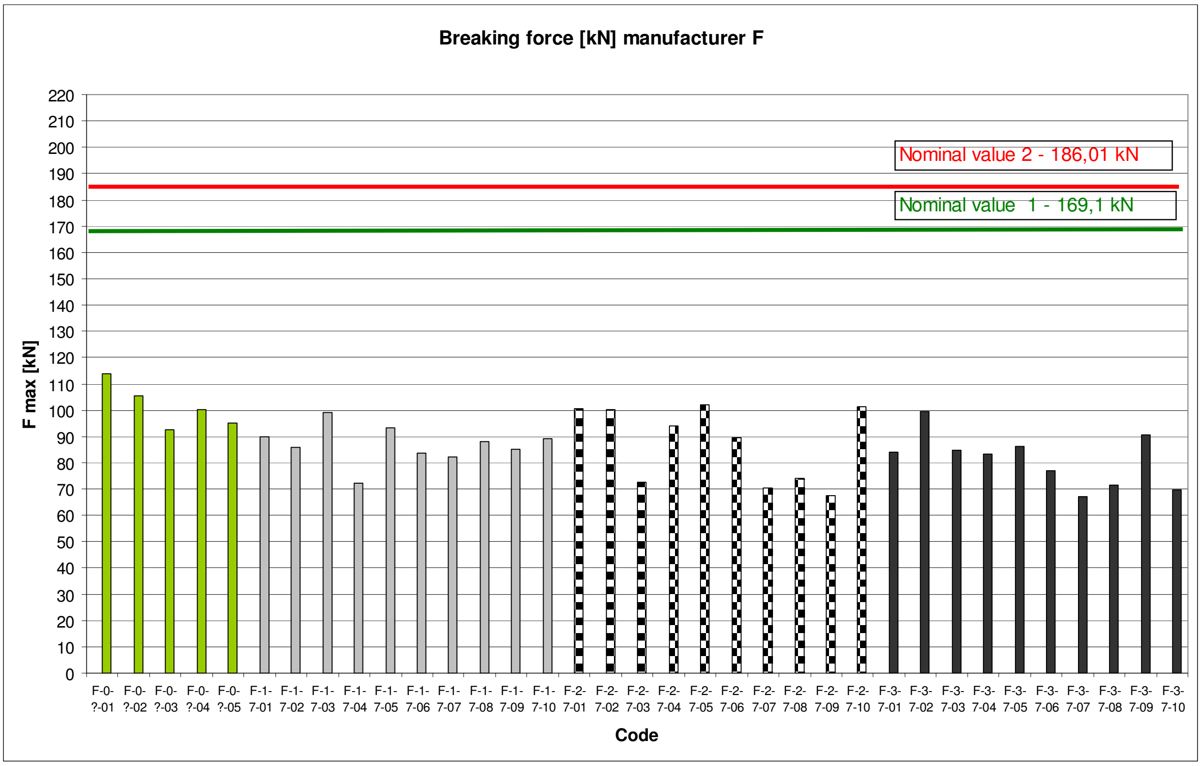


Figure 32: Test results of manufacturer F

The test results of manufacturer F are over all categories (new, 1 year, 2 year, 3 years) on a nearly constant level but with a high deviation to the nominal value 1 = 169,1 [kN]. For all tested nets only 18 hooks were applied.
It seems that the threads of the ropes are closely woven. This might be advantageous concerning the ageing processes. The threads may have a smaller surface against penetration of UV-Light and/or a higher resistance against imbedded particles.

6.3.6 Manufacturer G

All planned nets of each category of manufacturer G could be tested. It means:

- new nets 5 pieces
- 1 year old 10 pieces
- 2 years old 10 pieces
- 3 years old 10 pieces

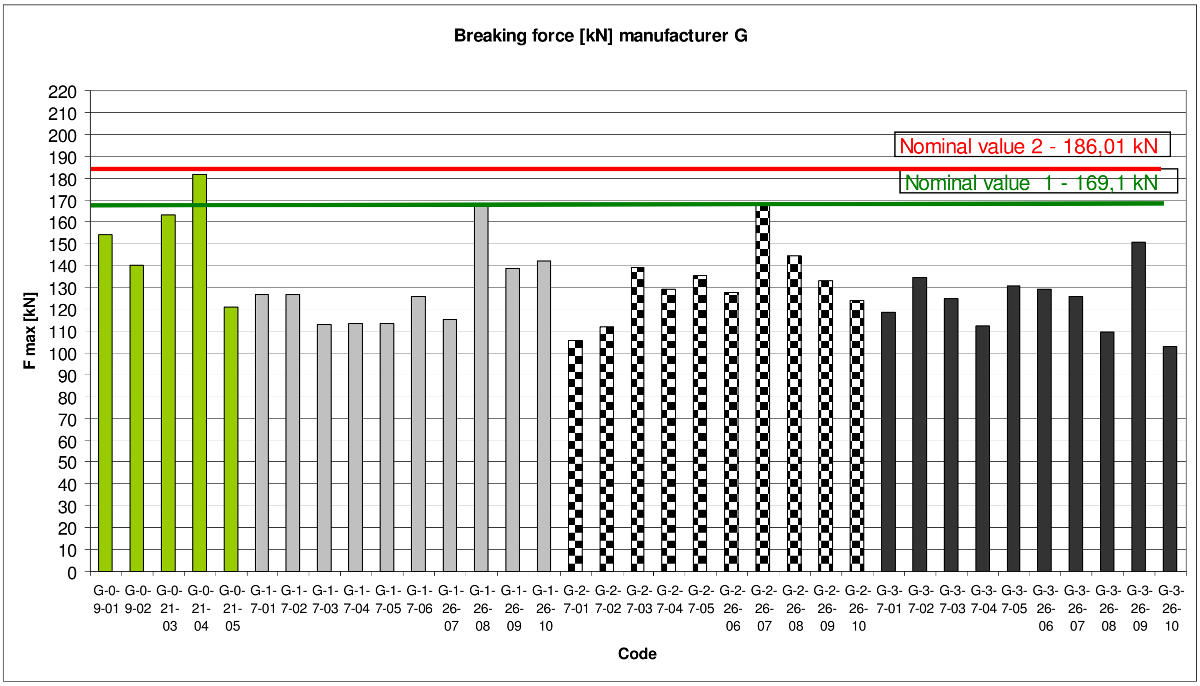


Figure 33: Test results of manufacturer G

Also the test results of manufacturer G are over all categories (new, 1 year, 2 year, 3 years) on a nearly constant level but with higher deviation to the nominal value 1 = 169,1 [kN]. During the tests it was detected that in many cases the failure mode was the hook. Either the hook itself was destroyed or the net broke close to a hook.

6.3.7 Category H – Other tests

Number and types of reefing hooks

During the net tests of different net manufacturers two different aspects concerning the hooks were detected.

- The number of hooks (on the 96” side) differs between 4 and 5 and on the 125” side between 5 and 7 hooks.
- The quality of the hooks differs from manufacturer to manufacturer. Some hooks were damaged (ruptured) during the tests, some were bent and others did cut the ropes of the net.

To further evaluate the influence of reefing hooks some additional net tests were made with variation of number of hooks and/or using other hooks (shackles).

The complete results of these tests are shown in annex 4.

- Test of a new net of manufacturer A with 24 hooks instead of 18 hooks – higher load.
- Test of 4 new nets of manufacturer B with 24 other hooks (shackles) – all nets reached more than 200 [kN].
- Test of 1 one year old net of manufacturer B with 24 hooks instead of 18 (18 original hooks and 6 additional other hooks) – the nominal value 1 = 169,1 [kN] was reached.
- Test of 3 new nets of manufacturer C with original 24 hooks (maybe a new net type of manufacturer C?) – deviation to the nominal value 1 only 2,1 to 8,5 [%]
- Test of 1 one year old net of manufacturer C with 24 instead of 18 hooks – higher load.

4 years old nets

During net acquisition 5 nets of manufacturer D with an age of 4 years were collected. But only two could be tested because three were not repaired. One net (age 47 month) reached 115,6 [kN] and the other (age 47 month) 154,6 [kN]. It was suspected that these nets were not often used in service.

5 years old nets

During net acquisition 2 nets of manufacturer A with an age of 5 years were collected. One net (age 63 month) reached 117,6 [kN] and the other (age 64 month) 161,5 [kN]. It was also suspected that these nets were not often used in service.

Nets without date of manufacturer

During net acquisition some nets were delivered without date of manufacturer. All these nets were in service and had been repaired. It could be suspected that the labels may have been lost during repair.

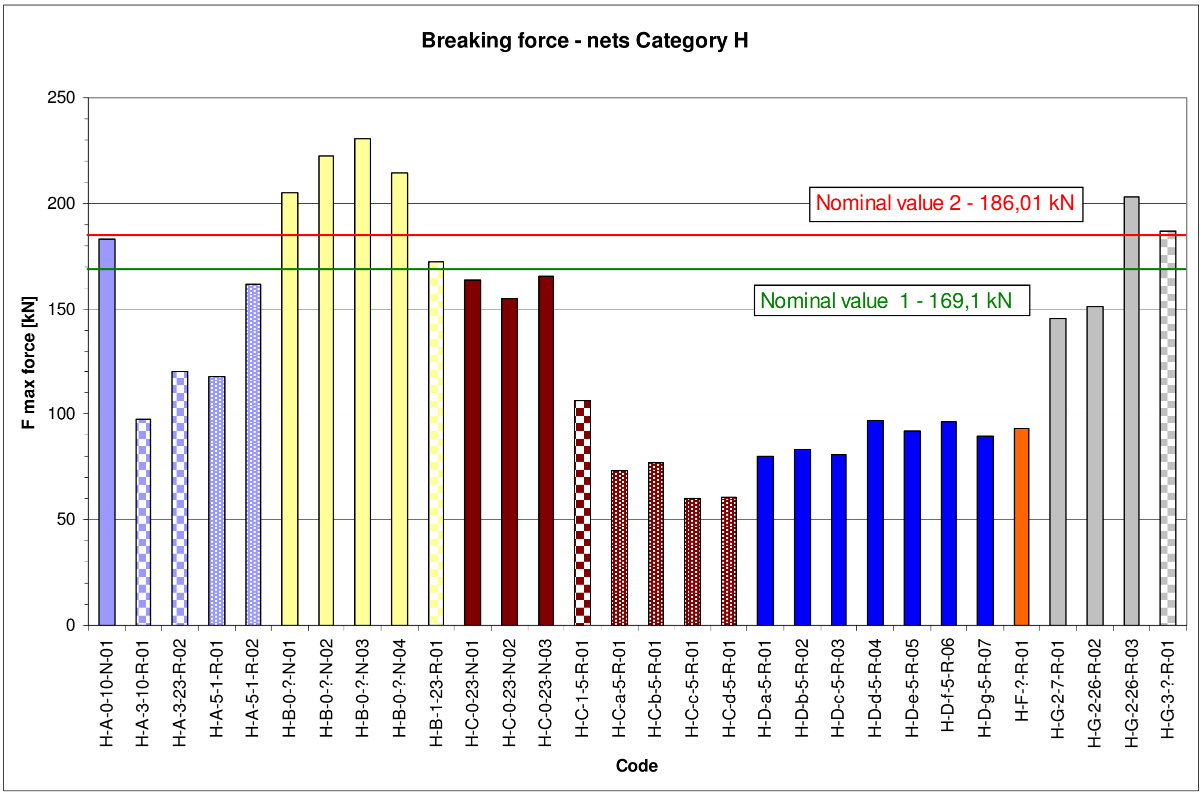


Figure 34: Test results of category H

6.4 Analysis net age / failure mode

For the net acquisition the following 4 categories should be considered:

- new nets
- 1 year old nets
- 2 years old nets
- 3 years old nets

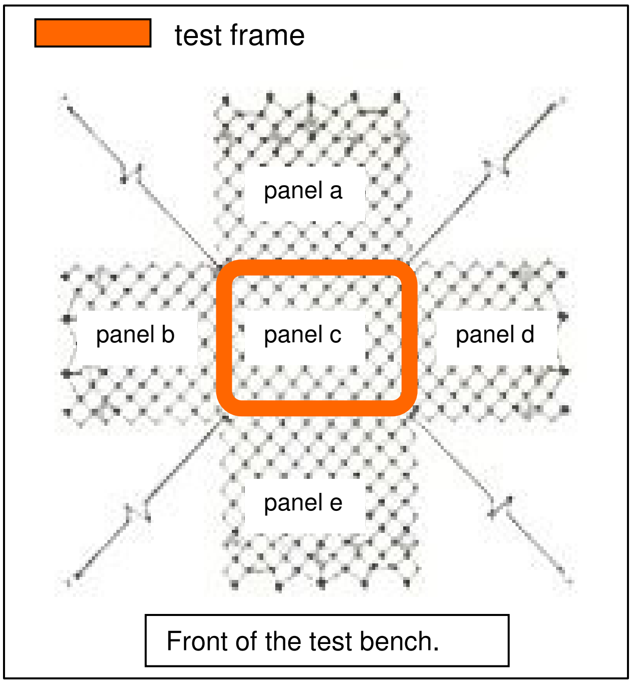
The age of nets (service life time) was defined as from date of manufacturing (month/year) until arrival of the nets at STFI e.V. (month/year).

During the net procurement it became clear that it is impossible to get nets with an age of exactly e.g. 12 month. Therefore a time window was specified:

1 year: 8 – 16 month
2 years: 20 – 28 month
3 years: 32 – 40 month

Annex 3 contains an overview of the age of all tested nets.

For all tested nets the place of the failure was noted (annex 3). For that different criteria were established (see figure 35). The reason for that was to find out any weak points of the nets. Additionally this documentation can be also used for verification of the test bench. If all nets would have broken in the same place, this could have been an indication for a fault in the test bench. This was clearly not the case. The failures are documented in annex 3.



panel	Net/Splice/knot	Net broke at/ close to …				hook rupture
		Frame	stud	Corner	Hook	
a	-	1	-	-	-	1
b	-	-	-	-	-	-
c	-	-	1	-	-	-
d	-	-	-	-	-	-
e	-	-	-	-	-	-

Figure 35: Scheme of net and table for documentation of failure modes

Statement to figure 35 (only example for explanation, no real test data):

- 3 nets tested
- 1 net broke close to frame at panel a
- 1 net broke close to stud at panel c
- 1 hook rupture panel a

6.5 Notes to the examinations

In the following the characteristics and facts detected during the net tests are specified.

- Different textile fabrics for the nets are used (woven or braided ropes).
- Knotted and knotless (spliced) nets are used.
- Nets with different weight are used (12 – 20 kg).
- A different numbers of reefing hooks were applied.
- The labelling differs by the manufacturer (Labels of metallic, plastic, paper protected in plastics).
- Almost all tested used nets had been repaired at least one time.
- Older nets appeared some times less used than younger nets (the time of the first entry into service of the net is not recognizable).
- The way of wrapping the net (especially bundling of studs and lashing lines) for packaging purposes is done in different qualities. It may have an influence in praxis when the ropes are entangled. It takes more time to handle the nets.
- Repaired areas cannot automatically be considered to represent weak points.
- Some manufacturers have different types (e.g. light weight, standard, heavy duty) under one certification approval (ETSO/JTSO); it means nets with different part numbers for the net category 2M2N.
- A statement with respect to different strength degradation as a result from use (treatment) by different airlines cannot be made without speculation, because the different airlines use also different manufacturers/nets/part numbers.
- On some manufacturers nets the hooks are found to be the weak points (hooks cut the rope, hook bent open or hook rupture).
- In some cases the nets (ropes, braids) appeared to be slightly damaged by heat, maybe a thermal cutter was used by the repair station.
- On some nets no date of manufacturing was available.
- The net construction of one manufacturer is not deforming symmetrical under load because the hook position is not optimal. The hook is placed in such a way that the main load acts on one mesh side only and not on both mesh sides.

7 Outcomes and Conclusions

The aim of this study was to investigate the strength degradation of fabric particular used for air cargo nets. Main focus of the investigation was to compare and evaluate strength degradation of air cargo nets due to their life time and usage which could be presented in this report.

The project was carried out within 15 month and was divided in three phases.
Phase 1 Net acquisition
Phase 2 Net testing and analysis
Phase 3 Final report

A representative number of nets size 2M2 (per NAS 3610 – Rev. 10 [1]: 96” x 125”) was purchased including controlled in-service-data. In total 210 nets of six different manufacturers and different service-times were tested systematically to get a set of representative results.

The acquisition of nets was challenging - in some cases easy in others very difficult because the support by airlines/leasing station/repair station with used nets was depending on their willingness to support this investigation. As described, some changes in net acquisition were considered necessary.

For the net testing a computer controlled test rig according to STFI internal testing procedure was applied. With this test equipment a full-scale test of the complete net is possible. The advantages of the complete net tests are that all single parts of the nets (lashing lines, reefing hooks, studs, knots) and the interaction of all ropes are considered during testing. The main results of this project are the following:

- Six net manufacturers could be covered with sufficient statistical data for testing used nets to investigate strength degradation.
- The net constructions and the weight of the nets vary extensively.
- The weight of the net has a significant influence on the reached load.
- A strength degradation of air cargo nets as a result of their use (ageing processes) up to more than 50 % was detected.
- Already in the first year during the life of a net the highest strength degradation was detected.
- Most of the tested used nets did not reach the required nominal value according to NAS 3610 Rev. 10 (167,1 [kN]).
- Only 6,7 % of the tested new nets did reach that value according to NAS 3610 Rev. 10 (167,1 [kN]).
- The number of reefing hooks has a big influence on the results.
- On the nets of some manufacturers the hooks have been found to be the weakest points.
- All elements (ropes, hooks, …) can be only considered in their combination by a full scale test.

- The real stress during life of an individual net can be only estimated (climate conditions, number of flights) because many different influences may have to be considered in strength degradation.

As result of the study, a data base of more then 200 systematically net tests (made under full scale tests) is available for the first time world wide. So the study offers a very good basis for further decisions concerning testing, certification, rulemaking, approval and standardisation of air cargo nets.

Beside the obtained tested results, the investigation itself can not explain in full detail the real structural behaviour of polymers in the degradation process. The results of the investigation are based on theoretical and experimental studies. But the linkage of both is difficult because the overlapping influencing parameters can not be clearly identified. The systematically experimental testing is an iterative and empiric method to prove the hypothesis made in theoretical study. But on the basis of the results achieved, all involved parties (manufacturers, certification authorities, test departments, …) should be able to continue the work for further solutions.

8 Recommendations

- A method for full scale testing of cargo nets should be specified (standardisation procedure) and become a basis for future cargo net certifications.

- The method to be recommended for all net certifications should also contain design details of a representative and acceptable test set-up and the test procedure to be applied.

- During testing the reefing hooks would have to be applied because the investigation has shown that such missing parts can be an additional weakness.

- The certification of a net should only be based on a full scale test in accordance with the above amended test method because only this would guarantee reliable results.

- A service life time limitation of the nets is recommended. This concerns not only the total life time of net starting from date of manufacturing (DOM), including duration of storage and the real service life. It should include also the number of flights because the mechanical impact while usage has a strong influence on degradation as shown in the investigation.

- The date of when the net goes into service for the first time would be important to register because as explained in the study, the effect of physical aging is applying immediately after the DOM. The strength degradation is happening in the very first months of the life time even during storage due to the change in molecular structure of polymers. Therefore, a system should be installed to differentiate between date of manufacturing (DOM) and the actual date when the net is brought in-service. It should be added on the manufacturing label, maybe best by qualified airline staff.

- It could happen that a net after a certain age had degraded to an inacceptable level because of unfavourable conditions (for example exposure to very high temperature and UV light) without ever have been in-service but this is only a speculation and would need further investigations.

- The condition for the storage of nets should be dark, dry and at suitable temperatures (e.g. 15-20 °C) as recommended in literature [4] and especially used for textile constructions to be preserved.

- All manufacturers should install a quality control system (testing or occasional sample checks in production). If no qualified test rig for a full scale test would be available, the tests on ropes, ropes in connection with studs and hooks should be applied only in their full combination. This could be done by using a test machine for tensile test.

- The systems of labelling should be improved. It is to ensure that all needed information on the net are visible up to the end of its life time. It has been shown in the investigation that DOM labelling was for some nets insufficient.

- The nets of the size 2M2 should be equipped with 24 reefing hooks (96” panels with 5 hooks each, 125” panels with 7 hooks each) because of a more even load distribution.

- The hooks should be placed in such a way that the load is preferable acting on both mesh sides for symmetrical deformation.

- For a theoretical approach to the subject the EN 12195-2 [19] (Load restraint assemblies on road vehicles – Safety – Part 2: Web lashing made from man-made fibres) could be used.

- A defined packaging procedure of the nets (way of wrapping the net especially bundling of studs and lashing lines) should be recommended and define how to store the nets in between the flight cycles.

- A storage system for the net handling should be recommended - first in – first out (to be applied by manufacturers and airlines).

- It is to clarify who would be responsible for taking nets out of service (airline, repair station?) and more important what conditions would apply to consider a net to be still airworthy. This could become a standardized procedure for operators and may be linked to the repair manuals/maintenance documentations.

- Further investigation should consider the elongation of the nets (to consider also height of cargo and height of the cargo compartments).

9 Final remarks

It was an honour for the STFI e.V. to carry out this project. We would like to thank the colleagues of EASA, in particular Mr. Kleine-Beek, Mr. Singer and Mr. Görnemann for their precise support and suggestions.
The authors also would like to thank their colleagues for the engaged support in this project.

The STFI is interested and ready to support this topic in the future and to work actively in this matter with all interested parties.

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List of figures

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Annex 1

Work schedule

Work schedule – Evaluation of strength degradation of fabric particularly used for cargo nets

	M 1	M 2	M 3	M 4	M 5	M 6	M 7	M 8	M 9	M 10	M 11	M 12	M 13	M 14	M 15
WP 1: Kick-off meeting at STFI (contract, approach, test procedure, test device…)															
WP 2: Purchasing nets (purchasing, marking / anonymization, storage, …)															
WP 3: Start testing (e.g. all brand new nets = reference, and 2 nets of the different service life time															
WP 4: Interims report (evaluation of the 1st results, further test will be agreed)															
WP 5: Testing (according to the results of the interims meeting)															
WP 6: Preparing the draft study report															
WP 7: Draft study report to EASA															
WP 8: Final study report to EASA															
Meetings															
Kick-off															
Interims meeting															
Final meeting															
Milestone 1: contract, Kick-off meeting															
Milestone 2: interims report															
Milestone 3: final study report															

Annex 1

Annex 2

Overview of all test results

Manufacturer	Age [year(s)]	Code	Fmax [kN]	Deviation [%] to the nominal value1 = 169,1 [kN]	Mass [kg]	mean value [kN]
A	new	A-0-10-01	135,9	-19,6	14,16	138,4
A	new	A-0-10-02	126,2	-25,4	14,44	
A	new	A-0-10-03	153,0	-9,5	14,46	
A	new	A-0-?-04	168,2	-0,5	14,01	166,3
A	new	A-0-?-05	164,4	-2,8	13,98	
A	1	A-1-1-01	165,3	-2,2	18,67	155,7
A	1	A-1-1-02	145,3	-14,1	18,57	
A	1	A-1-1-03	169,0	-0,1	18,77	
A	1	A-1-1-04	143,0	-15,4	18,53	
A	1	A-1-7-05	83,6	-50,6	14,33	81,2
A	1	A-1-10-06	66,1	-60,9	14,66	
A	1	A-1-10-07	77,1	-54,4	14,57	
A	1	A-1-10-08	106,9	-36,8	14,43	
A	1	A-1-10-09	79,5	-53,0	14,43	
A	1	A-1-10-10	74,1	-56,2	14,62	
A	2	A-2-1-01	161,3	-4,6	18,71	177,1
A	2	A-2-1-02	205,2	21,3	18,73	
A	2	A-2-1-03	164,9	-2,5	18,75	
A	2	A-2-10-04	106,2	-37,2	16,22	108,4
A	2	A-2-10-05	109,4	-35,3	16,04	
A	2	A-2-10-06	104,0	-38,5	15,61	
A	2	A-2-10-07	104,4	-38,3	16,02	
A	2	A-2-10-08	118,2	-30,1	15,97	
A	2	A-2-1-09	160,9	-4,8	18,56	158,3
A	2	A-2-1-10	155,7	-7,9	18,78	
A	3	A-3-7-01	84,9	-49,8	13,90	92,0
A	3	A-3-7-02	81,2	-52,0	14,03	
A	3	A-3-7-03	87,9	-48,0	13,85	
A	3	A-3-7-04	109,5	-35,2	14,19	
A	3	A-3-7-05	96,3	-43,1	13,83	
A	3	A-3-1-06	133,9	-20,8	18,49	144,1
A	3	A-3-1-07	153,0	-9,5	18,16	
A	3	A-3-1-08	152,1	-10,1	18,21	
A	3	A-3-1-09	137,2	-18,9	18,43	
A	3	A-3-10-10	121,3	-28,3	15,80	121,3
B	new	B-0-11-01	150,4	-11,1	17,94	150,4
B	new	B-0-?-02	140,6	-16,9	17,44	158,0
B	new	B-0-?-03	169,6	0,3	17,56	
B	new	B-0-?-04	152,2	-10,0	17,94	
B	new	B-0-?-05	169,5	0,2	17,58	
B	1	B-1-0-01	119,8	-29,2	20,36	122,4
B	1	B-1-0-02	129,4	-23,5	19,70	
B	1	B-1-0-03	117,9	-30,3	19,84	
B	1	B-1-0-04	100,3	-40,7	16,93	100,3
B	1	B-1-0-05	121,3	-28,3	19,81	121,3
B	1	B-1-4-06	140,3	-17,0	18,00	125,9
B	1	B-1-4-07	130,6	-22,8	17,94	
B	1	B-1-4-08	129,9	-23,2	17,67	
B	1	B-1-4-09	112,7	-33,4	17,89	
B	1	B-1-4-10	116,0	-31,4	17,84	
B	2	B-2-0-01	78,2	-53,8	19,82	91,0
B	2	B-2-0-02	103,8	-38,6	19,96	
B	2	B-2-24-03	103,3	-38,9	19,49	103,3
B	2	B-2-16-04	105,9	-37,4	18,11	118,9
B	2	B-2-16-05	131,9	-22,0	17,91	
B	2	B-2-4-06	153,1	-9,5	17,83	137,7
B	2	B-2-4-07	107,7	-36,3	18,08	
B	2	B-2-4-08	152,3	-9,9	17,84	
B	2	B-2-3-09	110,9	-34,4	18,28	110,9
B	2	B-2-4-10	106,8	-36,8	18,11	106,8
B	3	B-3-16-01	116,7	-31,0	18,23	110,8
B	3	B-3-16-02	104,8	-38,0	17,86	
B	3	B-3-3-03	116,8	-30,9	18,45	116,8
B	3	B-3-3-04	111,3	-34,2	18,43	111,3
B	3	B-3-4-05	118,5	-29,9	18,33	109,2
B	3	B-3-4-06	99,2	-41,3	18,01	
B	3	B-3-4-07	103,8	-38,6	17,92	
B	3	B-3-4-08	115,1	-31,9	18,37	
B	3	B-3-3-09	121,7	-28,0	18,00	121,7
B	3	B-3-3-10	122,1	-27,8	17,94	122,1

Manufacturer	Age [year(s)]	Code	Fmax [kN]	Deviation [%] to the nominal value1 = 169,1 [kN]	Mass [kg]	mean value [kN]
C	new	C-0-5-01	119,3	-29,5	12,20	130,7
C	new	C-0-5-02	101,1	-40,2	12,11	
C	new	C-0-5-03	150,3	-11,1	12,13	
C	new	C-0-5-04	145,3	-14,1	12,10	
C	new	C-0-5-05	137,6	-18,6	12,20	
C	1	C-1-5-01	63,7	-62,3	12,30	68,1
C	1	C-1-5-02	75,6	-55,3	11,88	
C	1	C-1-5-03	63,3	-62,6	12,70	
C	1	C-1-5-04	71,1	-58,0	11,97	
C	1	C-1-5-05	67,0	-60,4	12,50	
C	1	C-1-23-06	120,1	-29,0	12,36	112,2
C	1	C-1-23-07	96,4	-43,0	12,23	
C	1	C-1-23-08	120,0	-29,0	12,24	
C	1	C-1-23-09	113,6	-32,8	11,73	
C	1	C-1-25-10	110,8	-34,5	12,10	
C	2	C-2-5-01	62,0	-63,3	12,30	60,3
C	2	C-2-5-02	58,5	-65,4	12,30	
D	new	D-0-9-01	177,3	4,8	15,42	170,2
D	new	D-0-9-02	163,0	-3,6	15,44	
D	new	D-0-5-03	141,5	-16,3	14,10	149,7
D	new	D-0-5-04	161,1	-4,7	14,20	
D	new	D-0-5-05	146,6	-13,3	14,20	
D	1	D-1-5-01	114,4	-32,3	13,97	92,0
D	1	D-1-5-02	103,2	-39,0	14,40	
D	1	D-1-5-03	73,2	-56,7	14,30	
D	1	D-1-5-04	86,1	-49,1	14,49	
D	1	D-1-5-05	83,3	-50,7	14,16	
D	1	D-1-11-06	115,0	-32,0	15,08	115,0
D	2	D-2-27-01	72,1	-57,4	15,56	72,1
D	2	D-2-16-02	169,5	0,2	18,90	158,9
D	2	D-2-16-03	150,5	-11,0	19,00	
D	2	D-2-16-04	156,7	-7,3	18,98	
D	2	D-2-5-05	88,2	-47,8	14,56	89,4
D	2	D-2-5-06	92,2	-45,5	14,76	
D	2	D-2-5-07	95,7	-43,4	14,71	
D	2	D-2-5-08	81,3	-51,9	15,10	
D	2	D-2-16-09	135,2	-20,0	18,46	123,8
D	2	D-2-16-10	112,4	-33,5	18,87	

Manufacturer	Age [year(s)]	Code	Fmax [kN]	Deviation [%] to the nominal value1 = 169,1 [kN]	Mass [kg]	mean value [kN]
F	new	F-0-?-01	114,0	-32,6	14,12	101,5
F	new	F-0-?-02	105,5	-37,6	14,11	
F	new	F-0-?-03	92,6	-45,2	14,00	
F	new	F-0-?-04	100,2	-40,7	14,00	
F	new	F-0-?-05	95,2	-43,7	14,20	
F	1	F-1-7-01	89,8	-46,9	14,74	86,8
F	1	F-1-7-02	85,8	-49,3	14,62	
F	1	F-1-7-03	99,1	-41,4	14,67	
F	1	F-1-7-04	72,2	-57,3	14,93	
F	1	F-1-7-05	93,1	-44,9	14,61	
F	1	F-1-7-06	83,8	-50,4	14,72	
F	1	F-1-7-07	82,2	-51,4	14,63	
F	1	F-1-7-08	87,9	-48,0	14,63	
F	1	F-1-7-09	85,2	-49,6	14,63	
F	1	F-1-7-10	89,3	-47,2	14,68	
F	2	F-2-7-01	100,5	-40,6	15,68	87,3
F	2	F-2-7-02	100,3	-40,7	15,58	
F	2	F-2-7-03	72,7	-57,0	15,67	
F	2	F-2-7-04	93,9	-44,5	15,71	
F	2	F-2-7-05	102,1	-39,6	15,81	
F	2	F-2-7-06	89,6	-47,0	15,60	
F	2	F-2-7-07	70,5	-58,3	15,75	
F	2	F-2-7-08	74,0	-56,2	16,00	
F	2	F-2-7-09	67,5	-60,1	15,66	
F	2	F-2-7-10	101,4	-40,0	15,29	
F	3	F-3-7-01	83,9	-50,4	15,85	81,4
F	3	F-3-7-02	99,4	-41,2	15,86	
F	3	F-3-7-03	84,7	-49,9	15,98	
F	3	F-3-7-04	83,4	-50,7	15,93	
F	3	F-3-7-05	86,4	-48,9	15,89	
F	3	F-3-7-06	77,0	-54,5	15,77	
F	3	F-3-7-07	67,0	-60,4	15,75	
F	3	F-3-7-08	71,6	-57,7	15,63	
F	3	F-3-7-09	90,8	-46,3	15,83	
F	3	F-3-7-10	69,8	-58,7	16,01	
G	new	G-0-9-01	154,0	-8,9	14,23	147,1
G	new	G-0-9-02	140,1	-17,1	14,22	
G	new	G-0-21-03	163,1	-3,5	18,38	155,2
G	new	G-0-21-04	181,6	7,4	19,95	
G	new	G-0-21-05	121,0	-28,4	19,81	
G	1	G-1-7-01	126,6	-25,1	14,75	119,8
G	1	G-1-7-02	126,9	-25,0	14,91	
G	1	G-1-7-03	112,8	-33,3	14,88	
G	1	G-1-7-04	113,2	-33,1	14,87	
G	1	G-1-7-05	113,4	-32,9	14,77	
G	1	G-1-7-06	125,8	-25,6	15,06	
G	1	G-1-26-07	115,1	-31,9	18,27	141,1
G	1	G-1-26-08	168,4	-0,4	17,96	
G	1	G-1-26-09	138,7	-18,0	18,60	
G	1	G-1-26-10	142,0	-16,0	18,18	
G	2	G-2-7-01	105,7	-37,5	14,90	124,3
G	2	G-2-7-02	112,1	-33,7	14,67	
G	2	G-2-7-03	139,2	-17,7	14,31	
G	2	G-2-7-04	129,3	-23,5	14,63	
G	2	G-2-7-05	135,4	-19,9	14,32	
G	2	G-2-26-06	127,9	-24,4	18,24	139,5
G	2	G-2-26-07	168,1	-0,6	18,12	
G	2	G-2-26-08	144,6	-14,5	18,10	
G	2	G-2-26-09	132,9	-21,4	18,25	
G	2	G-2-26-10	123,9	-26,7	17,76	
G	3	G-3-7-01	118,5	-29,9	14,44	124,1
G	3	G-3-7-02	134,6	-20,4	14,36	
G	3	G-3-7-03	124,6	-26,3	14,59	
G	3	G-3-7-04	112,3	-33,6	15,00	
G	3	G-3-7-05	130,4	-22,9	14,62	
G	3	G-3-26-06	129,1	-23,7	18,16	123,5
G	3	G-3-26-07	125,8	-25,6	18,32	
G	3	G-3-26-08	109,4	-35,3	18,23	
G	3	G-3-26-09	150,6	-10,9	18,20	
G	3	G-3-26-10	102,6	-39,3	18,21	

"?" - Airline unknown

Annex 3

Age of the nets and failure modes

manufacturer A

1. Age of nets

agreed between EASA & STFI - age defined as: **date of manufacture** up to **date of receival at STFI**

new	**5**

1 year

age in months														
7	8	9	10	11	12	13	14	15	16	17	18	19	20	**qty.**
							5	2	3					**10**
	10									in window				**10**

2 years

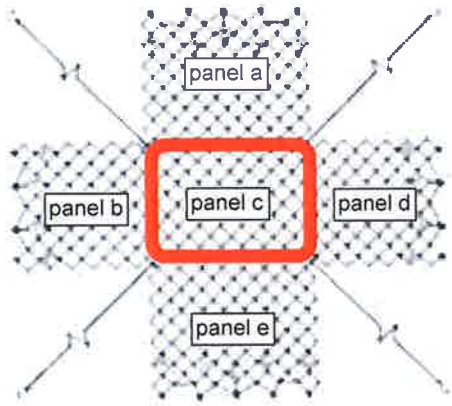
age in months														
19	20	21	22	23	24	25	26	27	28	29	30	31	32	**qty.**
						1	5	4						**10**
	10									in window				**10**

3 years

age in months														
31	32	33	34	35	36	37	38	39	40	41	42	43	44	**qty.**
						4	6							**10**
	10									in window				**10**

2. Failure modes

test frame



Front of the test bench.

panel	Net/Splice/knot	Net broke at/ close to ...				hook rupture
		Frame	stud	Corner	Hook	
a	12	-	1	-	3	-
b	1	-	-	-	1	-
c	2	1	-	3	-	-
d	-	-	-	2	-	-
e	5	-	3	-	1	-

manufacturer B

1. Age of nets

agreed between EASA & STFI - age defined as: **date of manufacture** up to **date of receival at STFI**

new	**5**

1 year

age in months														
7	8	9	10	11	12	13	14	15	16	17	18	19	20	**qty.**
					4	1		1	3	1				**10**
	9									in window				**9**

2 years

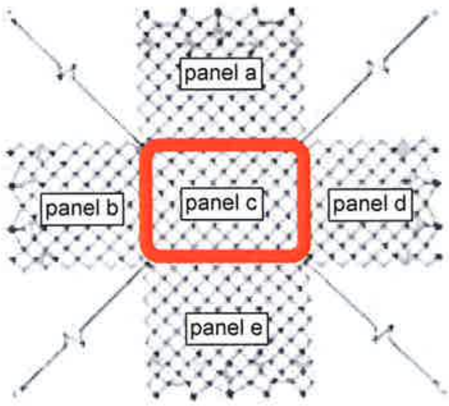
age in months														
19	20	21	22	23	24	25	26	27	28	29	30	31	32	**qty.**
					2	1	5		2					**10**
	10									in window				**10**

3 years

age in months														
31	32	33	34	35	36	37	38	39	40	41	42	43	44	**qty.**
			1	1	3	2	1	1					1	**10**
	9									in window				**9**

2. Failure modes

test frame



Front of the test bench.

panel	Net/Splice/knot	Net broke at/ close to ...				hook rupture
		Frame	stud	Corner	Hook	
a	9	-	2	-	4	1
b	2	-	-	-	2	-
c	-	-	-	-	-	-
d	-	-	-	-	-	-
e	6	-	-	-	7	2

manufacturer C

1. Age of nets

agreed between EASA & STFI - age defined as: **date of manufacture** up to **date of receival at STFI**

new	**8**

1 year

age in months														
7	8	9	10	11	12	13	14	15	16	17	18	19	20	**qty.**
			3				4		2	1				**10**
	9									in window				**9**

2 years

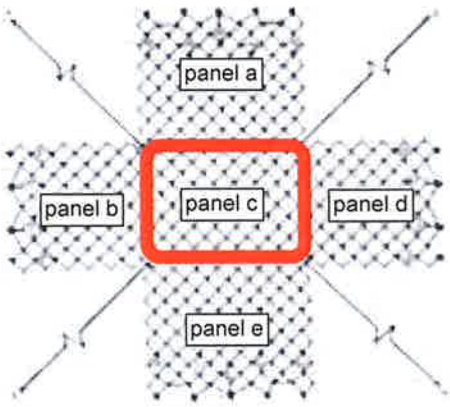
age in months														
19	20	21	22	23	24	25	26	27	28	29	30	31	32	**qty.**
			1		1									**2**
	2									in window				**2**

3 years

age in months														
31	32	33	34	35	36	37	38	39	40	41	42	43	44	**qty.**
														0
	0									in window				**0**

2. Failure modes

test frame



Front of the test bench.

panel	Net/Splice/knot	Net broke at/ close to ...				hook rupture
		Frame	stud	Corner	Hook	
a	-	-	-	-	5	-
b	-	-	-	-	3	-
c	3	-	-	3	-	-
d	-	-	-	-	1	-
e	-	-	-	-	5	-

manufacturer D

1. Age of nets

agreed between EASA & STFI - age defined as: **date of manufacture** up to **date of receival at STFI**

new	**5**

1 year

age in months														
7	8	9	10	11	**12**	13	14	15	16	17	18	19	20	**qty.**
			2			1		2			1			**6**
	5									in window				**5**

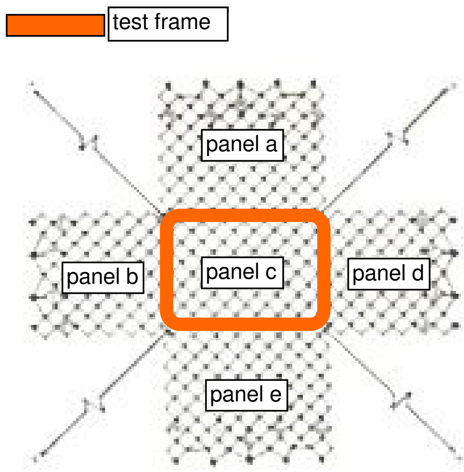
2 years

age in months														
19	20	21	22	23	**24**	25	26	27	28	29	30	31	32	**qty.**
	2	2	1	2					2		1			**10**
	9									in window				**9**

3 years

age in months														
31	32	33	34	35	**36**	37	38	39	40	41	42	43	44	**qty.**
														0
	0									in window				**0**

2. Failure modes



Front of the test bench.

panel	Net/Splice/knot	Net broke at/ close to …				hook rupture
		Frame	stud	Corner	Hook	
a	-	-	1	-	3	-
b	-	-	-	-	-	-
c	-	-	1	2	-	-
d	-	1	-	-	2	1
e	-	-	3	-	7	-

manufacturer F

1. Age of nets

agreed between EASA & STFI - age defined as: **date of manufacture** up to **date of receival at STFI**

new	**5**

1 year

age in months														
7	8	9	10	11	**12**	13	14	15	16	17	18	19	20	**qty.**
					2	6		2						**10**
	10									in window				**10**

2 years

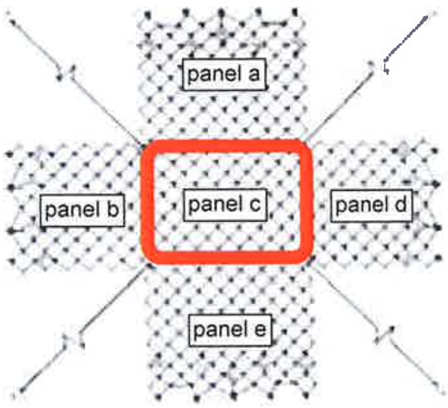
age in months														
19	20	21	22	23	**24**	25	26	27	28	29	30	31	32	**qty.**
		2			2	2	1	2	1					**10**
	10									in window				**10**

3 years

age in months														
31	32	33	34	35	**36**	37	38	39	40	41	42	43	44	**qty.**
		1						4	5					**10**
	10									in window				**10**

2. Failure modes

test frame



Front of the test bench.

panel	Net/Splice/knot	Net broke at/ close to ...				hook rupture
		Frame	stud	Corner	Hook	
a	2	1	-	1	6	-
b	-	-	-	-	4	-
c	2	-	-	1	-	-
d	-	-	-	1	4	-
e	1	1	-	2	9	-

manufacturer G

1. Age of nets

agreed between EASA & STFI - age defined as: **date of manufacture** up to **date of receival at STFI**

new	**5**

1 year

age in months														
7	8	9	10	11	12	13	14	15	16	17	18	19	20	**qty.**
				1	2	2	1	1	1	1	1			**10**
	8									in window				**8**

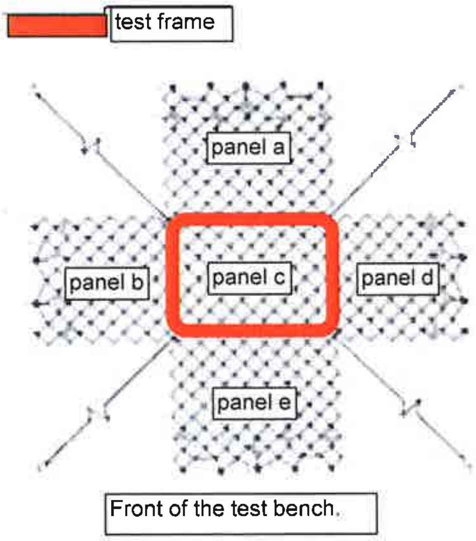
2 years

age in months														
19	20	21	22	23	24	25	26	27	28	29	30	31	32	**qty.**
2		1			1	1	1	2	1	1				**10**
	7									in window				**7**

3 years

age in months														
31	32	33	34	35	36	37	38	39	40	41	42	43	44	**qty.**
1	1		1	2			1	3	1					**10**
	9									in window				**9**

2. Failure modes



panel	Net/Splice/knot	Net broke at/ close to ...				hook rupture
		Frame	stud	Corner	Hook	
a	2	-	-	-	-	2
b	-	-	-	-	6	1
c	2	-	-	1	-	-
d	2	-	2	2	2	5
e	2	-	1	1	4	-

Annex 4

Results H - other

Manufac-turer	Age [year(s)]	Code	Fmax [kN]	Deviation [%] to the nominal value1 = 169,1 [kN]	Mass [kg]	remaks (Why tested in the category "H-others")
A	new	H-A-0-10-N-01	182,8	8,1	14,37	24 instead 18 hooks
A	3	H-A-3-10-R-01	97,7	-42,2	15,76	24 instead 18 hooks
A	3	H-A-3-23-R-02	120,4	-28,8	14,18	24 instead 18 hooks
A	5	H-A-5-1-R-01	117,6	-30,5	17,70	5 years old
A	5	H-A-5-1-R-02	161,5	-4,5	19,75	5 years old
B	new	H-B-0-?-N-01	204,7	21,1	17,46	other hooks (shackle)
B	new	H-B-0-?-N-02	222,6	31,6	17,47	other hooks (shackle)
B	new	H-B-0-?-N-03	230,7	36,4	17,50	other hooks (shackle) and 26 hooks (shackle) instead 18
B	new	H-B-0-?-N-04	214,3	26,7	17,48	other hooks (shackle)
B	1	H-B-1-23-R-01	172,0	1,7	17,89	24 instead 18 hooks
C	new	H-C-0-23-N-01	163,3	-3,4	11,28	net type with 24 hooks
C	new	H-C-0-23-N-02	154,8	-8,5	11,32	net type with 24 hooks
C	new	H-C-0-23-N-03	165,5	-2,1	11,34	net type with 24 hooks
C	1	H-C-1-5-R-01	106,7	-36,9	12,20	24 instead 18 hooks
C	?	H-C-a-5-R-01	73,5	-56,5	13,00	without date of manufactuerer
C	?	H-C-b-5-R-01	77,3	-54,3	12,06	without date of manufactuerer
C	?	H-C-c-5-R-01	60	-64,5	12,71	without date of manufactuerer
C	?	H-C-d-5-R-01	60,5	-64,2	12,36	without date of manufactuerer
D	?	H-D-a-5-R-01	80,3	-52,5	15,14	without date of manufactuerer
D	?	H-D-b-5-R-02	83,1	-50,9	14,85	without date of manufactuerer
D	?	H-D-c-5-R-03	81	-52,1	14,84	without date of manufactuerer
D	?	H-D-d-5-R-04	97,1	-42,6	14,70	without date of manufactuerer
D	?	H-D-e-5-R-05	92	-45,6	14,90	without date of manufactuerer
D	?	H-D-f-5-R-06	96,7	-42,8	14,75	without date of manufactuerer
D	?	H-D-g-5-R-07	89,3	-47,2	14,93	without date of manufactuerer
D	4	H-D-4-37-R-01	115,6	-31,6	11,78	4 years old
D	4	H-D-4-37-R-04	154,6	-8,6	11,89	4 years old
F	1	H-F-?-R-01	93,6	-44,6	14,66	26 instead 18 hooks
G	2	H-G-2-7-R-01	145,5	-14,0	14,93	28 instead 18 hooks
G	2	H-G-2-26-R-02	150,7	-10,9	18,56	hooks replaced by shackle
G	2	H-G-2-26-R-03	203	20,0	18,16	hooks replaced by shackle
G	3	H-G-3-?-R-01	186,6	10,3	17,85	hooks replaced by shackle

For additional hooks shackle where used.

Annex 5

Photos of net testing

Photos of net testing

Typical net break

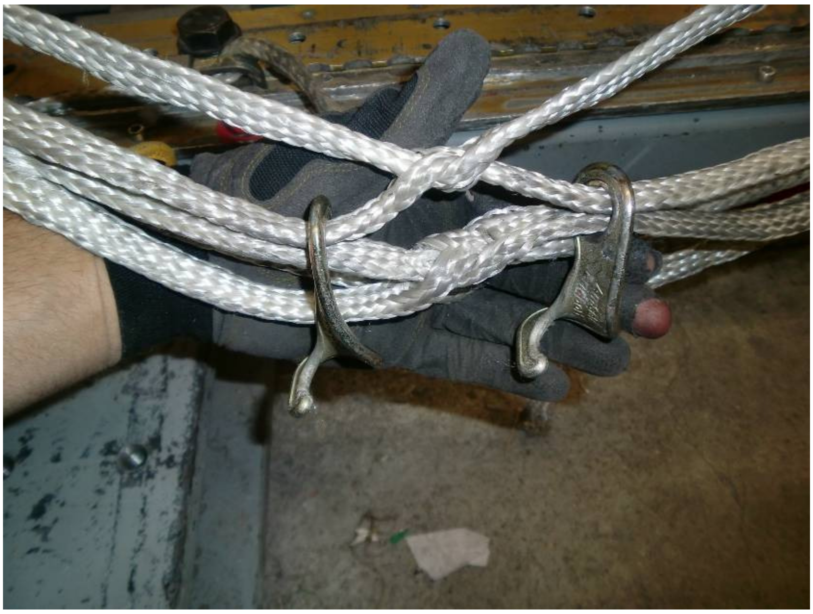
Influence of the hook

Cut by hook

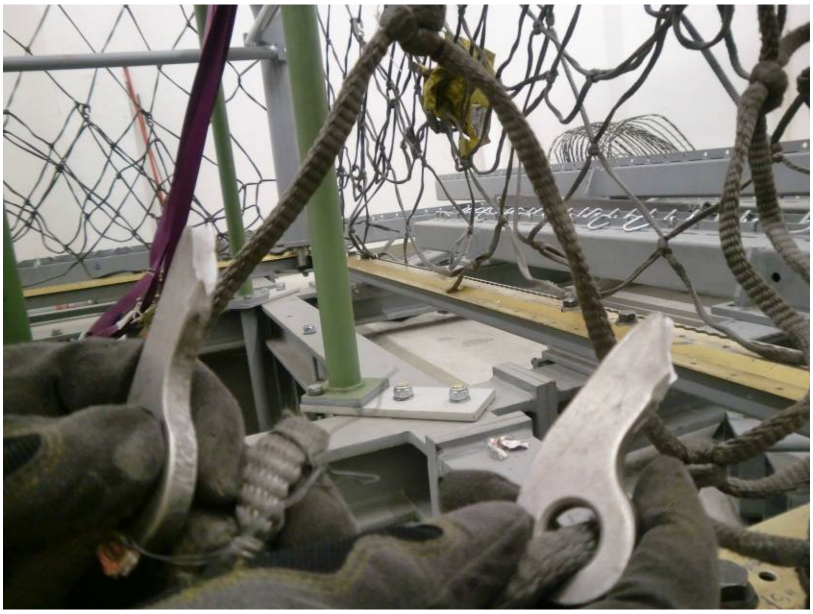
Failure on stud

Hooks replaced by shackle (category H)

Sample of use of shackle (category H)



Hooks - bent open



Hook rupture