# Requirements and Design Criteria for Cargo Restraint Systems

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## Introduction

The objective of this document is to outline design conditions and requirements for cargo restraint systems and to provide guidance to cargo handlers for using energy absorbing cargo restraints. Energy absorbing cargo restraints must satisfy requirements pertaining to normal maneuvering flight conditions and crash conditions. Guidelines for cargo handlers with regards to load preparation are provided through restraint tables that can be used for several different cargo handling scenarios. Regression models were also created from the restraint table data to provide cargo handlers with a set of equations to use to configure a crashworthy energy absorbing cargo restraint system.

Load limiters are incorporated to create energy absorbing restraints to replace elastic restraints (e.g., steel chains, nylon straps). Using load limiters allows restraints to dissipate energy and reduce forces transmitted to the airframe, but with a certain amount of stroke as shown in Figure 1. The cargo restraint configuration is selected in a manner that prevents cargo displacement in normal flight conditions. Furthermore, the amount of allowable cargo displacement – which is also dependent on the cargo restraint configuration – is constrained by cabin space, cargo placement, and crew seat locations.

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| Figure 1. Comparison of force-stroke response for elastic and energy absorbing restraints. |

## Design Conditions and Requirements

A crash is a singular event and is considered the worst-case scenario which drives cargo restraint system design. Cargo restraint systems, however, must also be designed to provide safety in situations which may produce lower acceleratory loads, but occur on a regular basis. Therefore, the requirements for cargo restraint systems are twofold: 1) Restrain cargo to a fixed position in normal maneuvering flight conditions; 2) Arrest cargo motion within an allowable displacement in a crash.

### Normal Maneuvering Flight Conditions

For the requirements proposed in this report, the normal maneuvering flight conditions are defined as the conditions experienced in recurring flight operations; where the loads on the cargo are induced by the acceleration from takeoff, maneuvers, gusts, and landing. The cargo restraint system must restrain the cargo to a fixed position, within some tolerance due to elongation of the lanyards, and while keeping the restraint forces below the activation force of the load limiter. The amount the cargo is allowed to displace due to lanyard elongation will be dependent on the mission and cargo handling scenario.

Prohibiting cargo movement in normal maneuvering flight operations will prevent injuries and avoid interference with crew operations which may require personnel to move around inside the cargo cabin area. The load factors to be used in the static analysis can be obtained from existing load preparation documents. The FM 55-450-2 field manual in particular provides load factors of 4 G and 1.5 G in the longitudinal and lateral directions, respectively. These load factors are based upon the operating conditions experienced on U.S. Army rotorcraft.

### Crash Conditions

The crash conditions refer to an event which can result in significant damage to the aircraft, occupant injuries and/or fatalities. The Aircraft Crash Survival Design Guide and MIL-STD-1290 are used as a reference for the crash conditions and loads to be used in the design of cargo restraint systems. The velocity change requirements at impact are 13 m/s and 6.5 m/s in the longitudinal and lateral directions, respectively. The acceleration at the cabin floor is approximated as a triangular pulse with a peak of 16 G and 10 G in the longitudinal and lateral directions, respectively.

For energy absorbing cargo restraint systems, the key requirement in crash conditions is to be able to arrest the motion of the cargo without violating an allowable displacement constraint. The allowable displacement can be unique to each cargo handling scenario and is dependent on several factors including aircraft type, location of the cargo, and location of occupants. At the very least, the cargo displacement must be constrained to prevent the cargo from moving into occupied space and injuring crew members. Additionally, the cargo should not be allowed to impinge on areas of the airframe structure which are essential to providing a protective occupant envelope.

## Usage Guidance

It is unlikely that cargo handlers will have the time or resources to conduct analytical studies prior to load preparation. One possible solution is the use of prepared tables to provide guidance on configuring restraint systems for a variety of cargo handling scenarios. An example restraint table was created which features energy absorbing restraints combining nylon straps and steel chain with a tear webbing device (i.e., load limiter). A cargo dynamics simulation is used to generate the restraint tables and the input parameters which define the cargo handling scenarios are shown in Table 1. The tear webbing device has an activation force of 44.5 kN and a maximum load limiter stroke of 1.2 m. Furthermore, the tie-down configurations were simplified to be doubly symmetric. All restraints were tied down at an angle of 30/30.

Table 1. Restraint table parameters and values.

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| --- | --- |
| Parameter | Range of Values |
| Activation Force | 44.5 kN |
| Max. Stroke | 1.2 m |
| Restraint Type | Steel Chain/Tear Webbing, Nylon Strap/Tear Webbing |
| Direction | Longitudinal, Lateral |
| Cargo Weight | 22.2 kN 🡪 88.9 kN |
| Crash Pulse Peak | 4 G 🡪 16 G (Longitudinal), 1.5 G 🡪 10 G (Lateral) |
| Impact Velocity | 10 m/s 🡪 13 m/s (Longitudinal),4.4 m/s 🡪 6.4 m/s (Lateral) |
| Cargo Displacement | 10 cm 🡪 150 cm (Steel Chain/Tear Webbing),  50 cm 🡪 200 cm (Nylon Strap/Tear Webbing) |

A sample restraint table is shown in Table 2. The output of the restraint table is the number of restraints required and the corresponding maximum load limiter stroke of each restraint. The number of restraints is rounded up to the nearest multiple of four to have a doubly symmetric tie-down configuration. The example presented here requires more information regarding inputs that would be required in the field. Cargo handlers would not be required to define the crash condition parameters (e.g., pulse peak, impact velocity). The only information the cargo handlers will need to provide is the cargo weight, restraint type, and amount of allowable displacement.

Table 2. Sample restraint table for longitudinal impacts.

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Restraint Type | Steel Chain/Tear Webbing (Impact Velocity = 13 m/s) | | | | | | | | | | | |
| Longitudinal Pulse Peak | 4 G | | | 8 G | | | 10 G | | | 16 G | | |
| Allowable Displacement [m] | < 0.1 | < 1.0 | < 1.5 | < 0.1 | < 1.0 | < 1.5 | < 0.1 | < 1.0 | < 1.5 | < 0.1 | < 1.0 | < 1.5 |
| Cargo Weight | Number of Restraints Required | | | | | | | | | | | |
| 22.2 kN | 8 | 4 | 4 | 8 | 8 | 4 | 12 | 8 | 4 | 16 | 8 | 8 |
| 44.5 kN | 12 | 8 | 8 | 16 | 12 | 8 | 24 | 12 | 8 | 28 | 12 | 12 |
| 66.7 kN | 16 | 8 | 8 | 24 | 16 | 12 | 32 | 16 | 12 | 44 | 16 | 16 |
| 88.9 kN | 20 | 12 | 12 | 32 | 20 | 16 | 44 | 20 | 16 | 56 | 28 | 20 |

## Regression Model

Although the restraint tables eliminate the need to conduct a detailed analysis, cargo handlers will still have to sort through a large archive of restraint tables for one that corresponds to the desired scenario. To make things simpler, a regression analysis was conducted for the restraint table data to create a small set of simple equations which the cargo handlers can use to quickly select and configure the energy absorbing cargo restraint systems. A quadratic function with four input variables is used to model the dataset with four different equations corresponding to the two types of energy absorbing cargo restraints (steel chain/tear webbing, nylon strap/tear webbing) and two impact directions (longitudinal, lateral). The input variables of each equation include cargo weight, crash pulse peak, impact velocity, and allowable cargo displacement. The number of restraints required is the dependent variable of the regression model. The general form of the regression model is provided by the following equation:

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| --- | --- |
|  | (1) |

where *N* is the number of restraints required, *W* is the cargo weight, *PG* is the crash pulse peak, *D* is the allowable cargo displacement, and *V* is the impact velocity. The range of values for the allowable cargo displacement and impact velocity are dependent upon on the direction of impact. The coefficients (*bi*) of Eq. (1) for all four models can be found in Table 3.

Using the regression model is similar to the restraint tables. First, the user (e.g., cargo handler) must first choose a restraint type. The user will then calculate the number of restraints required for longitudinal and lateral impacts. For example, if the user chooses steel chain/tear webbing restraints (SC/TW), then the “SC/TW – Long.” and “SC/TW – Lateral” regression models will be used to determine the number of restraints required. The nylon strap/tear webbing regression models are labeled "NS/TW – Long." and "NS/TW – Lateral". However, the output of each regression model is the number of restraints required to satisfy the conditions for a single direction. Therefore, the larger of the two regression model solutions will determine the final number of restraints required to ensure that the restraint system is able to provide adequate safety in both directions.

Table 3. Regression models coefficients for steel chain/tear webbing (SC/TW) and nylon strap/tear webbing (NS/TW) for impact in the longitudinal and lateral directions.

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| --- | --- | --- | --- | --- |
| **Coefficients [units]** | **SC/TW – Long.** | **SC/TW - Lateral** | **NS/TW – Long.** | **NS/TW - Lateral** |
| *b1* | 1.956E+00 | 2.072E+00 | 3.294E+00 | 6.265E+00 |
| *b2* [N-1] | 2.986E-04 | 8.857E-06 | 1.269E-03 | 1.153E-03 |
| *b3* [m-1 s2] | 2.690E-01 | 5.815E-01 | 1.285E+00 | 1.389E+00 |
| *b4* [m-1] | 1.481E+00 | -4.272E+00 | -3.523E+01 | -3.247E+01 |
| *b5* [m-1 s] | -4.359E-01 | -1.447E-01 | 1.792E+00 | 2.636E+00 |
| *b6* [N-2] | 2.500E-09 | 5.333E-09 | 1.563E-10 | 1.042E-09 |
| *b7* [m-2 s4] | -1.944E-02 | -5.493E-02 | -8.281E-02 | -1.432E-01 |
| *b8* [m-2] | 6.915E+00 | 1.078E+01 | 2.501E+01 | 2.944E+01 |
| *b9* [m-2 s2] | -1.250E-02 | -6.667E-02 | -1.445E-01 | 1.641E-01 |
| *b10* [m-2 N-1 s2] | 6.108E-05 | 6.567E-05 | 9.513E-05 | 5.914E-05 |
| *b11* [N-1 m-1] | -6.680E-04 | -7.650E-04 | -1.811E-03 | -1.688E-03 |
| *b12* [N-1 m-1 s] | 5.987E-05 | 1.267E-04 | 1.509E-04 | 2.919E-04 |
| *b13* [m-3 s2] | -9.508E-01 | -1.478E+00 | -2.030E+00 | -1.741E+00 |
| *b14* [m-2 s3] | 8.289E-02 | 2.195E-01 | 2.565E-01 | 4.513E-01 |
| *b15* [m-2 s] | 6.339E-02 | -7.188E-01 | -7.033E-01 | -5.660E+00 |

The error of the regression model is calculated using Eq. (2), where *Predicted N* is the

output from the regression model and *Actual N* is the data from the restraint tables.

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| *Error = (Predicted N) – (Actual N)* | (2) |
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A negative error value corresponds to the model under-predicting the number of restraints required. A sample histogram depicts a Gaussian distribution in the error as shown in Figure 2. The same distribution can be seen in the histograms for the remaining three models. A lower standard deviation would decrease the likelihood of under-predicting the number of restraints required to provide adequate safety. Future efforts should incorporate statistical methodologies to ensure sufficient safety. A single load factor simply applied to all model predictions may prevent safety issues from under-predicting the number of restraints required, but there will be a higher probability of over-predicting the number of restraints required and creating issues regarding load preparation time and restraint system weight.

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| Figure 2. Histogram plot of the error from “SC/TW – Longitudinal” regression model. |