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## **SAILS-RIGGING BLAST PROTECTIVE STRUCTURAL SHIELD**

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### **SITUATION**

Terrorism is becoming more and more of a threat both at home and abroad, which requires adequate counter measures. It was widely believed until recently that a building subject to an explosive attack had a chance to remain standing only if it possessed some extraordinary resistive capacity (**Sassi et al.** 1998). This belief rested on the assumption that the specific impulse or the time integral of pressure, which is a dominant characteristic of the external blast load, is fully beyond our control. Fortunately, the last statement is just half-true. We, actually, cannot control a magnitude of a load itself but we can influence a timing of its application to structural elements as well as a pattern of interaction of those elements (**Shustov** 1998).

There is yet another way to shield internal premises of the building against air blast effects. The method is based on the concept of energy consumption, which means a temporary storage plus dissipation and dispersion, of window glass debris' kinematical energy with the help of a dispensable system called *Sails-Rigging Blast Protective Structural Shield* or, in short, **BPS** (**Shustov** 2001). **BPS** includes sails, pilasters and riggings (Figure 1).

Each sail consists of a vertical protective layer of a flexible and, at least partially, transparent fabric stretched internally parallel to windows between the external wall pilasters and running from the top of protected floors level of the building to its foundation. The pilasters divide external walls into the separate window protective sections. The riggings are vertical and horizontal (optional). The vertical riggings consist of array of parallel ropes, cables or rods supporting the sail membrane against the impact of glass debris. They represent the *tension components* of a rigging system. Floor diaphragms or horizontal riggings are the *compression components* of the system.

### **RESEARCH OBJECTIVES**

The objectives of the current research are to investigate the ability of the proposed *Sails-Rigging Blast Protective Structural Shield* to consume the kinetic energy of flying glass debris through the mechanism of plastic deformation of the tension of the system while transferring the rest of the blast energy to the whole building through the compression components of the system with a high resistive capacity in the range of elastic deformations.

The primary components of the **BPS** are disposable sails, made of partially transparent fabric, and cables, ropes or rods intended to support the sails against horizontal blast impact (Figure 1).

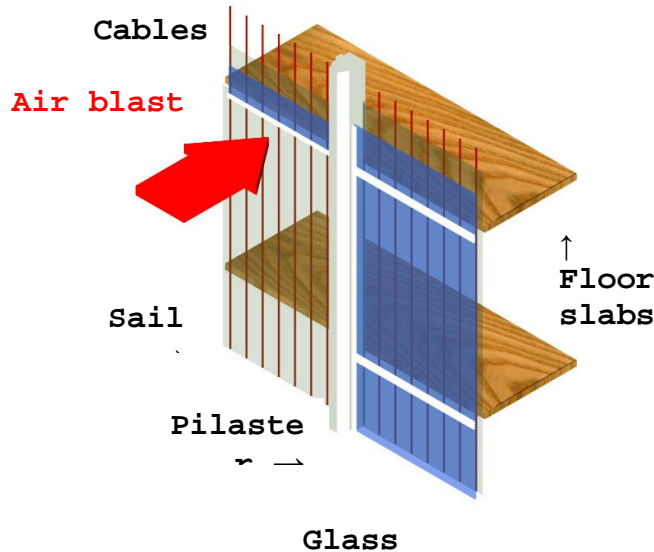


Figure 1. Fragment of BPS.

When a blast airwave reaches a glass window, it breaks up transforming the blast pressure impulse into kinetical energy of small debris that should be caught by the protective sail-rigging system. The sails and array of cables, ropes or rods make up the tension elements that may be approximated as flexible cables subject to equally distributed lateral loads. The primary distributed lateral loading on a vertical surface of the protected building structure may be represented by an air blast pressure and by its specific impulse which, according to **Crawford et al.** 1999, can reach up to 3,790 psi and 1,400 psi-ms, correspondingly.

The sail-rigging design approach is based on the assumption that there is no need to resist the huge pressure elastically. In a building equipped with **BPS**, the portion of the protective system that is exposed to an air blast shock wave may be sacrificed. The most attractive candidates as a material for **BPS** seem to be the non-reinforced composites that have considerable elongations at breaking loads. The matter is, both the tensile strength and maximum elongation contribute to the blast resistant mechanism of the system.

### ANALYTICAL APPROACH

Effectiveness of the blast energy mitigation may be characterized by the material *Specific Energy Consumption* parameter  $U_s$ , which represents an area under a tensile stress-strain curve of a sample of a unit length and cross-section area. Units of  $U_s = \text{lb}\cdot\text{in}/\text{in}^3$ .  $U_s$  is a cumulative parameter, which, actually, depends on the impact rate of strain. Fortunately, a high strain rates do not compromise the strength of composites (**Harding and Welsh** 1983, **Blazynski** 1987). Therefore, testing under a low rate loading may be used for a conservative estimation of the blast mitigating abilities of **BPS** components.

When the air blast impulse is applied to the glass window (Figure 1), the air pressure energy transforms into the kinetic energy of the broken glass particles. This energy, in its turn, should be transformed into the elastic energy of sail-rigging deformation minus the energy dissipated in a process of plastic deformation. A strip of the sail supported by ropes may be considered as a simple continuous system called a *string* or *cable*, which is

subjected to a transverse and equally distributed load. This load is a normal pressure on the external surface of the sail from the flying glass debris.

Thus, the mathematical model of sails (as well as that of ropes) is a completely flexible string acting as an axial member in tension (Figure 2).

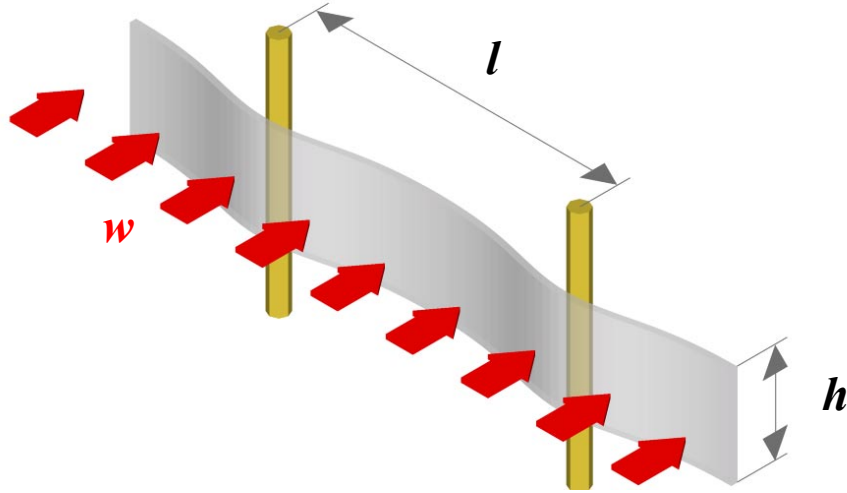


Figure 2. Pattern of sail deformation.

The maximum value of the Specific Impulse  $I_s$  applied to the vertical surface of the building may be expressed through the glass window related parameters:

$$I_s = m_{gl} v_{gl} = r_{gl} t_{gl} v_{gl} \quad (1)$$

where  $m_{gl}$  = mass of the glass of unit area;  
 $r_{gl}$  = glass density;  
 $t_{gl}$  = thickness of the glass;  
 $v_{gl}$  = glass debris initial velocity.

From equation (1), the initial debris velocity

$$v_{gl} = I_s / r_{gl} t_{gl} \quad (2)$$

In order the sail component of the system perform satisfactorily, the kinetic energy of glass debris  $E_k$  or the input energy (Chopra 1995) should not exceed the potential energy of the sail  $E_{br}$  at its breaking point, namely:

$$E_k \leq E_{br} \quad \text{or} \quad r_{gl} h l t_{gl} v_{gl}^2 / 2 \leq U_s h l t_f \quad (3)$$

where  $U_s$  = specific energy of sail deformation at breakage (Figure 2),  
 $t_f$  = thickness of sail fabric.

Using equations (2) and (3), obtain the *sail's integrity equation*:

$$I_s^2 \leq 2 r_{g1} t_{g1} t_f U_s \quad (4)$$

Equation (4) allows verifying protective ability of the sail's fabric as demonstrated in the Example 1 below.

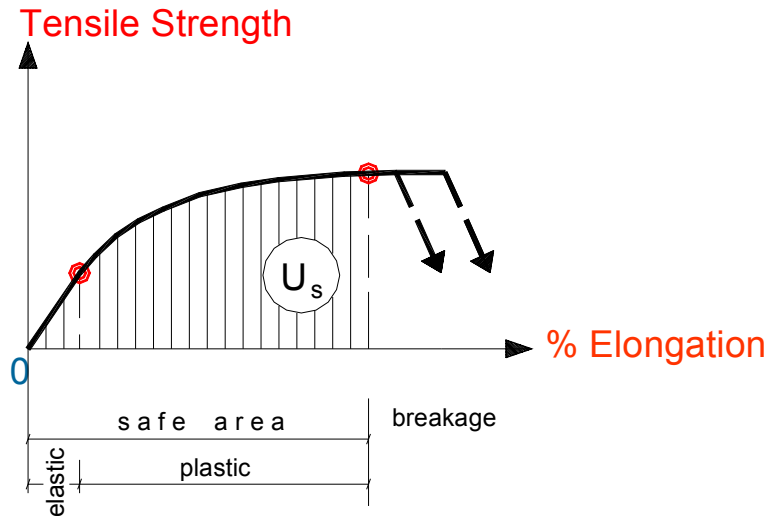


Figure 3. Hypothetical tensile strength-elongation curve.

**Example 1.** Check up the blast protective ability of a sail fabric made of Nylon 6 BS-10/BS-30 as a component of a BPS. Apply the following data:

$I_s = 1,400$  psi-ms,  $h = 1$  in,  $l = 12$  in,  $r_{g1} = 160$  lbm/ft<sup>3</sup>,  $t_{g1} = 0.5$  in,  $t_f = 0.075$  in,  $U_s = 6.012$  ksi-in/in.

From equation (4),

$$I_s = 1.40 \text{ psi-sec} \leq 1.87 \text{ psi-sec}$$

which means that the energy consuming mechanism of the sail fabric's deformation is adequate to neutralize the kinetic energy of blast debris.

Equation (4) yields up the following conclusions:

- Neither the ultimate tensile strength nor the maximum elongation can solely control the protective ability of the sail's material. Instead, it is their product or, more precisely, the specific energy consumption at the sail fabric's tensile deformation  $U_s$  (the area under the Tensile Strength - Elongation curve in Figure 3) that is the most crucial parameter.

- From the structural strength perspective, the span between the ropes or rods that support the sail is of no importance.

### DESIGN CRITERIA

However, besides the structural requirements, there is still occupational safety requirement imposed by the specific functional conditions in the premises immediately surrounded by the blast protective system.

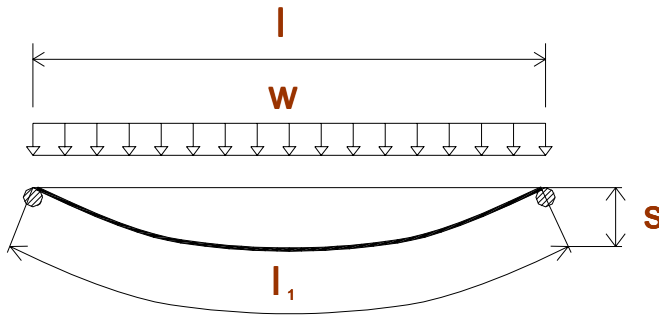


Figure 4. Mathematical model.

Assuming the distribution of the blast load per unit length  $w$  (Figure 4) is constant with respect to a horizontal line, the shape of the sail lateral deformation under a blast pressure or a window glass debris impact will be parabolic as that of a flexible cable under an equally distributed load  $w$  (Merritt 1989).

The approximate length (span) of the parabolic cable in result of the deformation characterized by the sag  $s$  is given by the equation (5).

$$l_1 = l + \Delta l = l [1 + 2.67 (2s/l)^2 - 1.6 (2s/l)^4] \quad (5)$$

Introducing into the equation (5) the term of elongation  $\epsilon = \Delta l / l$  and assuming that  $s$  should be equal to zero when  $\epsilon = 0$ , the following equation for the sag due to a plastic deformation is obtained:

$$s = 0.913 l [1 - (1 - 0.9 \epsilon)^{1/2}]^{1/2} \quad (6)$$

The horizontal sag value should be limited by the secure clearance between the bulged surface of the sail-rigging system, on one hand, and furniture, equipment or people location inside the protected premises, on the other. This requirement is illustrated in the Example 2.

**Example 2.** The ultimate elongation of the sail fabric during a blast impact  $\epsilon = 0.6$ . What is the ultimate sail's sag if  $l = 1'$ ?  $l = 15'$ ? Disregard the rigs' deformation.

From equation (6), receive:

- When  $l = 1'$ ,  $s = 0.518' = 6.21''$ .
- When  $l = 15'$ ,  $s = 7.77'$ .

Concerning the physical security of humans inside the protected premises, the last sag and, correspondingly, the span values will not be, most likely, acceptable.

## EFFECTIVENESS OF SAIL-RIGGING SYSTEM

The maximum pressure in the air blast transient wave, per **Crawford et al. 1999**, may reach  $w_{\max} = 3.79$  ksi. The effective value of pressure  $w$  that may develop during a sail deformation will be controlled by the plasticity mechanism.

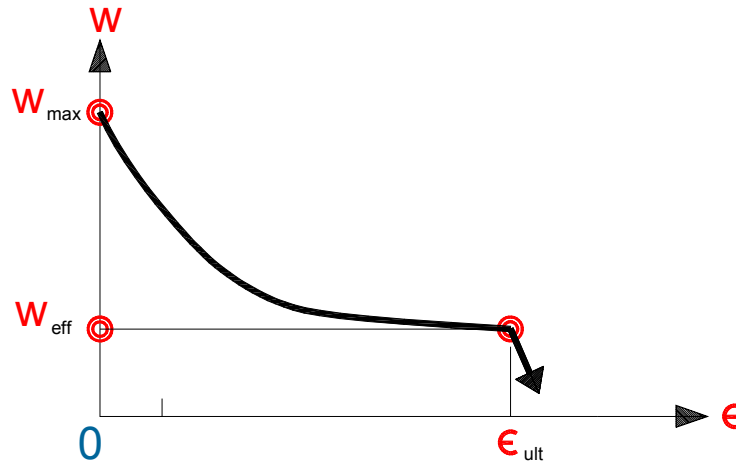


Figure 5. Curve  $w - \epsilon$ .

The tensile strength of a sail strip having width  $h$  and thickness  $t_f$  is equal:

$$T_{\text{eff}} = t_f h T \quad (7)$$

where  $T$  is the tensile strength of  $1 \text{ in}^2$  cross-section of the sail fabric. At the same time, as for a parabolic cable, the  $T_{\text{eff}}$  value is given by equation (8):

$$T_{\text{eff}} = (l w_{\text{eff}} / 2) [1 + (l / 4 s)^2]^{1/2} \quad (8)$$

Equating (7) and (8), obtain:

$$w_{\text{eff}} = \frac{2 t_f h T}{l [1 + (l / 4 s)^2]^{1/2}} \quad (9)$$

**Example 3.** The nylon strip (Figure 6) the blast protective ability of which was checked up in Example 1, has the following parameters:

$l = 12 \text{ in}; h = 1 \text{ in}; t_f = 0.1 \text{ in}; T = 11 \text{ ksi}; \epsilon = 0.6$ . The maximum blast pressure is  $w_{\max} = 3.79 \text{ ksi}$ .

is the value of  $w_{\text{eff}}$ ? How it differs from  $w_{\max}$ ?

Using equations (9) and (6), obtain:  $w_{\text{eff}} = 165 \text{ psi}$ . Thus, the blast pressure mitigating ratio is:

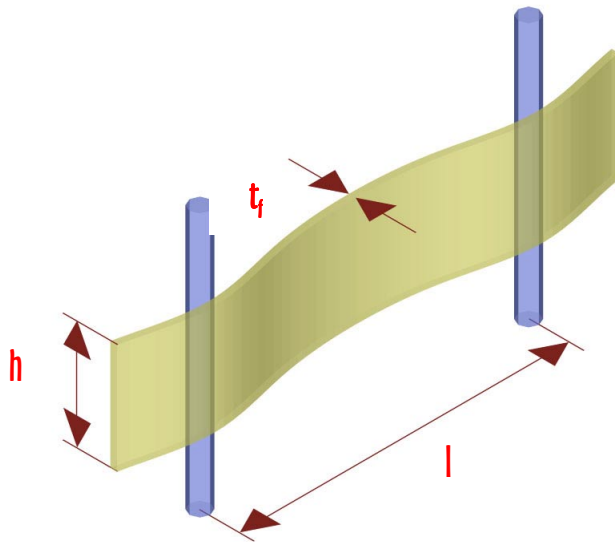


Figure 6. Sail strip under lateral load.

$$\frac{W_{\max}}{w_{\text{eff}}} = 3790 / 165 = 23 \text{ times}$$

which means that the horizontal load on the cables will decrease dramatically in the process of their plastic deformations.

**Example 4.** Using the data and results from Example 3, find out the linear lateral load per inch of a cable acting as a part of the rigging system:

$$W = w_{\text{eff}} l = 165 \cdot 1 \cdot 12 = 1980 \text{ lbs / in}$$

There is a difference between the linear load  $W$  applied to a cable and a similar load  $w_{\max}$  applied to the sail fabric. Whereas value of  $w_{\max}$  may be reduced to that of  $w_{\text{eff}}$  as a result of mechanical energy consumption in the form of energy dissipation and / or elastic deformation of the fabric, the cables may be requested to react statically to the full value of load  $W$  to prevent  $w_{\text{eff}}$  to go beyond the limits where the excessive sag of the cables will put the inhabitants' safety in jeopardy.

### ROPES, CABLES AND RODS TESTING

The laboratory static testing of tension components and their connections for the proposed design (Shustov 2001) was performed according to ASTM 1996 with the help of the United STM testing machine available at CSUN. The machine is composed of two interconnected yet separate components: the load frames where the actual testing of the specimen is performed and the computer, which controls the test process and handles all test data.

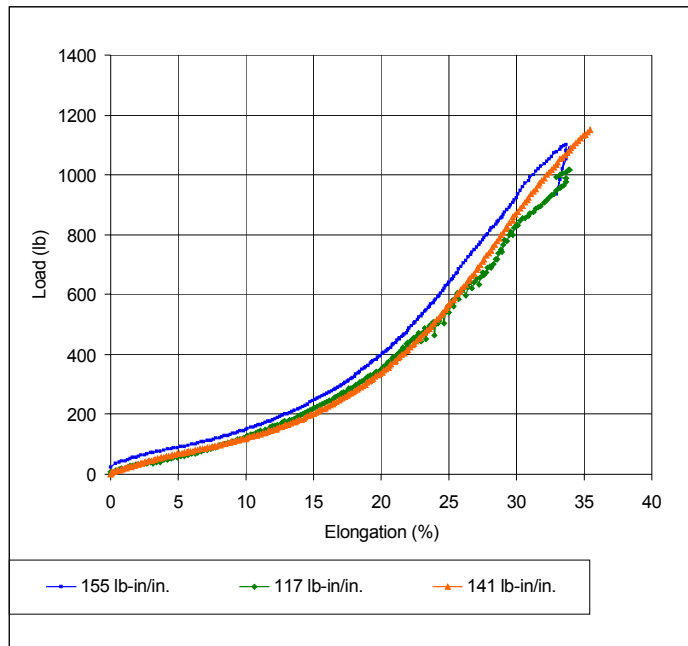


Figure 7. United STM testing machine.

The load frame utilizes a variable speed DC motor. Testing speed is controlled by two feedback loops. A DC tachometer provides instant feedback of motor speed to stabilize the servo loop and provide coarse control. The microcomputer senses and provides precise control of position and speed, strain, or load rate as required.

All testing of the tensile members took place under the following testing machine connections:

- Circular jaws (mostly for ropes).
- Thimbles on pins (for ropes and cables).
- Clamps (for rods).
- Clamps with coupling nuts (for rods).



The individual Charts like one presented in Figure 8 (see also a movie clip at **Shustov 2000**) were further used in process of quantitative analysis. Legends under the Charts present areas under the corresponding curves.

Figure 8. Test Chart 1a: 3/16" 3 Strand Premium Nylon Rope. Circular connection.

## CONCLUSIONS AND RECOMMENDATIONS

36 experiments comprising 147 individual tests were performed. A wide range of tested materials includes Nylon, polyethylene, ultra high molecular weight polyethylene, polypropylene, polyester, Technora, Vectrus, Aramid and Aracom, i.e. all those materials that have been used by the manufacturers of ropes. Nylon, polypropylene, polyester, and polycarbonate were used for rod specimen. The tested cables were made of steel.

Most of the ropes demonstrated rather high values of *Specific Energy Consumption* parameter: up to 5121 lb-in/in<sup>3</sup> for the Yale Yacht Braid 3/16" ropes, which may be considered the champion on still another parameter: *Resilient Elongation* (13.3% for the 5/16" ropes at the stress of 90% *Breaking Strength*). All maximum values of ropes strength, as well as of that of cables, occurred at the breaking point.

This is not the case for the rods, which collapsed at 60-70% maximum strength under the clamp connection conditions. The threaded connections of rods in cases when plasticity mechanism developed in the threaded portions of tested samples dramatically change the pattern of stress-elongation curves. However, when the rods connections were designed

properly, the plasticity mechanism occurred in the non-threaded portion of the rods and the connections did not influence the rods performance.

Some tested materials, while using in the rods, demonstrate extremely high values of *Specific Energy Consumption* parameter, namely: 10028 lb-in/in<sup>3</sup> for Polypropylene, 9029 lb-in/in<sup>3</sup> for Polyester, 7691 lb-in/in<sup>3</sup> for Nylon 6. However, these values develop as a result of huge elongations, namely: 503%, 155% and 88% correspondingly, which may jeopardize physical security inside the protected premises due to unacceptable sags of the sail-rigging system elements.

The issue of effectively connecting ropes, cables and rods for their integration into a protective system is a crucial issue for an adequate performance of BPS. It was our discretion to select connections and attachment schemes that seemed to be the most suitable for the catcher system and to test only them. Several types of those elements connections and their combinations were tried in course of the project.

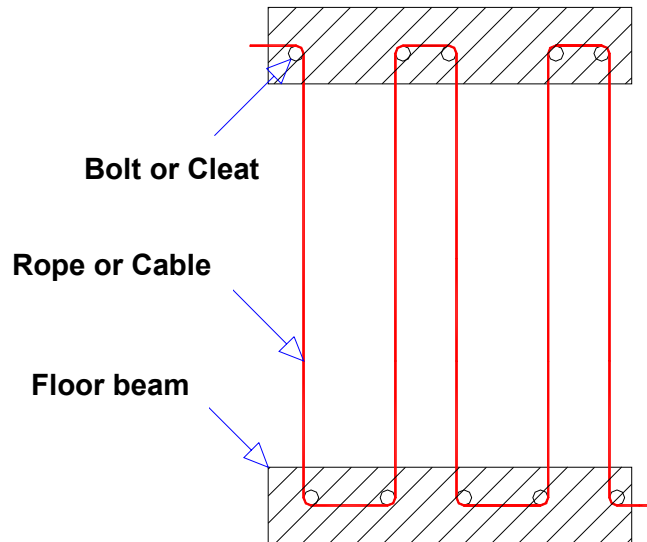


Figure 9. Serpentine cable system.

As a result, the following conclusions concerning the tested connections were made:

1. The best connection is no connection at all, like in the Continuous cable system presented in Figure 1 or Serpentine cable system in Figure 9.
2. Whenever connections are inevitable, use:
  - Splicing connections with thimbles for ropes.
  - Sleeved connections with thimbles for cables.
  - Clamp connections for rods.
3. Treaded connections with coupling nuts, if their design permits occurrence of the plasticity in threaded area of a rod, decrease both the active cross-section of the rod and its plastic performance.

Retrofit application of the proposed sails-rigging blast protective structural system, including the tension members and their connections, depends on the as-built conditions, magnitude of the anticipated explosion and its location, which may be specified in a process of practical design only. Therefore, these *Conclusions and Recommendations* presented here should be considered as general ones: they cannot substitute for the

consideration of the real field conditions. Nevertheless, one of the basic principles of *Sails-Rigging Blast Protective Structural Shield*, the method of *attaching* the system tension elements instead of *connecting* them, is, practically, universal.

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#### **LINKS:**

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