IV International Conference on Computational Methods for Coupled Problems in Science and Engineering
COUPLED PROBLEMS 2011
M. Papadrakakis, E. Oñate and B. Schrefler (Eds)

NON-LINEAR MODELLING, DESIGN AND PRODUCTION OF STEEL BLAST-RESISTANT DOORS AND WINDOWS

VALENTINA A. SALOMONI*, GIANLUCA MAZZUCCO*, GIOVANNA XOTTA*, RICCARDO L. FINCATO*, MARCO SCHIAVON, CARMELO E. MAJORANA***

*Department of Structural and Transportation Engineering
Faculty of Engineering, University of Padua
Via F.Marzolo, 9 – 35131 Padua, Italy
e-mail: salomoni@dic.unipd.it, mazzucco@dic.unipd.it, xotta@dic.unipd.it, fincato@dic.unipd.it, majorana@dic.unipd.it, www.dic.unipd.it

** Wellco S.p.A. Engineering and Construction,
v.le Mazzini 65/5, 31049 Valdobbiadene (TV), Italy
e-mail: m.schiavon@wellco.it, www.wellco.it

Key words: Blast, Impact, Plasticity, Steel doors.

Abstract. Numerical-experimental results are here described, derived from an innovative experience at both national and international level, related to modelling, designing and producing steel blast-resistant doors and windows. Their capability to sustain thermal loads due to fire hazards is additionally accounted for. The activity has been developed within a collaboration between Wellco S.p.A. and some researchers of the Department of Structural and Transportation Engineering of the University of Padua, Italy. The study has been conducted to define and characterize the non-linear response of a large number of doors and steel framed windows, with the objective of sustaining dynamic loads from explosive hazards of fixed magnitude, variable design and clearing times. The local overcome in the strength limit (with correspondent plastic response) and possible formation of plastic hinges has been critically discussed. Numerical models have allowed for refining first design sketches and subsequently understanding the real thermo-mechanical behaviour for the investigated structures. Experimental tests on typical steel doors at 1:1 scale have been performed at the Laboratory of Construction Materials of the same Department above. Such tests had the objective of "a-posteriori" verifying the correctness of the already available numerical results, validating the adopted procedures and correspondingly guaranteeing the doors' structural efficiency even under dynamic loads higher than design ones.

1 INTRODUCTION

The work comes from a joint collaboration in the field of Blast Resistant buildings, doors and windows. Particularly, steel doors and windows have been investigated following a request of an international client constructing gas plants in Eastern Europe.

Doors and windows effectively represent the most peculiar elements when designing blast resistant buildings, e.g. if their re-opening after explosion is requested for safety reasons (escape of personnel after the blast) [1]. Such an aspect is largely binding, essentially in the numerical modelling phases, being in fact its fulfilment to be guaranteed by controlling specific parameters. It is hence possible to admit that doors and windows enter the plastic regime (also considering that Ultimate Limit States are accounted for [1], [2]), but this requires additional verifications of well-defined ductility and rotation ratios. Consequently, the correct element behaviour is not affected and safety/rescue operations are ensured.

Doors and windows designed and constructed by Wellco S.p.A. are of various types and dimensions: from the one-shutter 1000×2000 mm^2 door up to larger 3500×4500 mm^2 ones.

In relation to doors and windows' dimensions [3]-[5], to value and duration of the explosive load (fixed), first design lines have been developed and subsequently the whole problem has been investigated by verifying procedures and characterizing the dynamic response of the structural elements. Non-linear (for material and geometry) analyses have been conducted also considering frames, joints, plates, hinges, glasses and opening devices. Procedures and methodology of analysis had already been known from a previous joint experience [6]-[9].

In the following the main results related to one door type only have been reported for sake of brevity, as well as the lines followed in agreement with International Recommendations; additional analyses, not described here, have also allowed for designing doors and windows under impulsive loads as well as thermal ones, satisfying the Italian requirements for REI60 or REI120.

2 F.E. MODELLING

2.1 Geometry

Finite Element models have been set up to simulate the door's behaviour in its closed configuration; beam-type elements have been used for defining the main structure (frame), **Figure 1**, whereas shell-type ones have characterized the internal and external steel plates.

Beam elements present a transversal section in agreement with the design one, to allow for defining a correct stiffness to internal and border elements (**Figure 2**); the number of horizontal stiffeners has been defined proceeding via a series of repeated analyses to obtain a structural response to guarantee the appropriate functional door's behaviour. Again, steel plates have been modeled to reproduce the design drawings (**Figure 3**).

2.2 Constraint conditions

Each shutter is connected to the edge wall through hinges (which number has been determined again via repeated analyses), modeled with rigid constraints to allow for free rotations. The counter-frame has been represented by the introduction of springs with equivalent stiffness, active in compression only; such a stiffness has been evaluated by considering a three-dimensional local model to which an imposed unit displacement has been applied (**Figure 4**). The contact between shutters has been additionally considered by interposing *link* elements, inactive if the response leads them to move away from each other (**Figure 5**), and closure points (representative of the real closure system, **Figure 6**).

During the *rebound* phase (qualifying the dynamic response and corresponding to the door bending in opposite direction with respect to the applied load) it has been assumed that the only active constraints are exclusively represented by closure points and hinges.

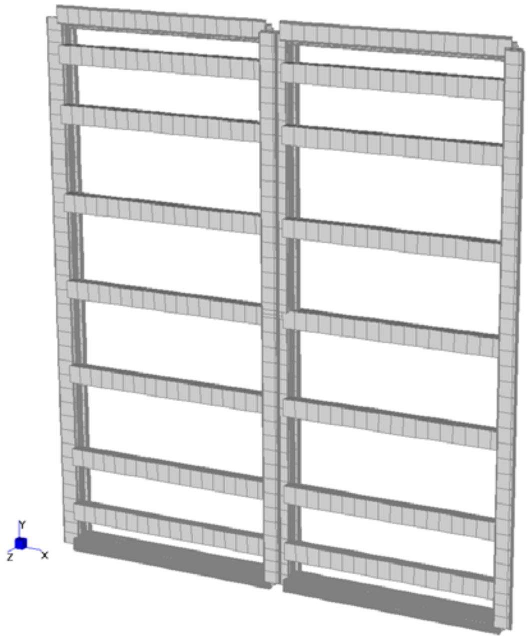

Figure 1: Main frame model, double shutter-type door.

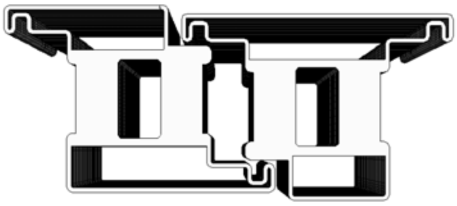

Figure 2: Internal and border elements.

Figure 3: Typical horizontal section.

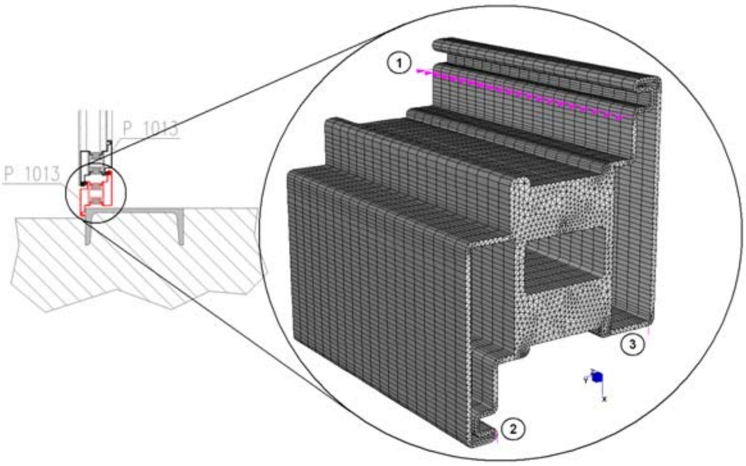

Figure 4: 3D model for counter-frame stiffness definition.

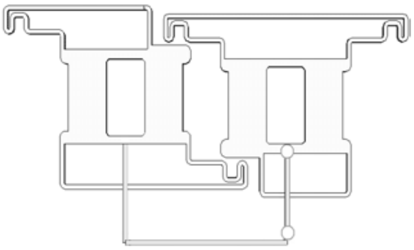

Figure 5: Shutter-to-shutter contact elements.

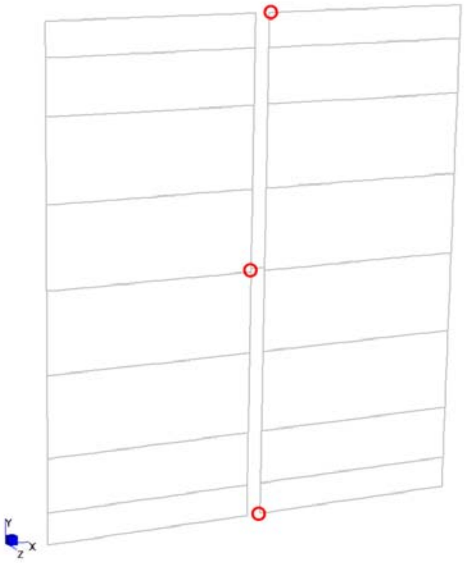

Figure 6: Schematic representation of closure points (in red).

2.3 Dynamic analyses

Once the (design) peak value of the blast load has been defined, as well as the time required for dissipating overpressure (t_d), it has been assumed to consider the impact of a plane frontal wave considering, in agreement with the Regulations, specific values for peak reflected pressure (P_r), stagnation pressure (P_s) and clearing time (t_c), realizing diagrams of the type of **Figure 7**.

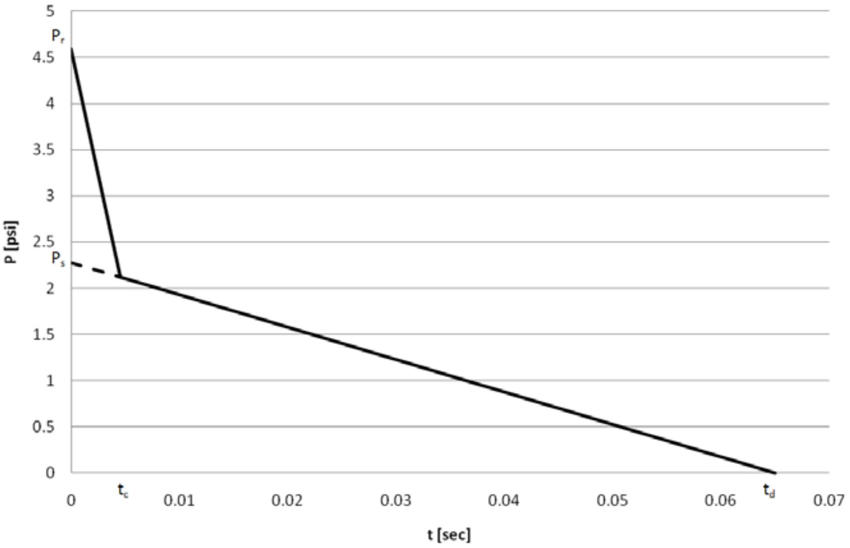

Figure 7: Typical pressure-time diagram for plane frontal blast wave.

The analyses have additionally included effects of dynamic damping to take into account a possible reduction in stress deriving from internal frictions and yielding of some elements; particularly, damping effects coming from the formation of plastic hinges have been represented by assigning an elasto-plastic behaviour to the material, whereas a fixed damping ratio has allowed for evaluating damping from internal frictions.

In **Figure 8** a typical displacement evolution in damped and undamped configurations is reported: the maximization of effects (peaks of maximum and minimum) is reached in both situations; this comes from the fact that the blast is rapidly exhausted (red curve) and the damping contribution is highlighted for longer times only (larger than t_d). Consequently, concerning the design phase, maximum actions only have to be considered and not the entire loading history; such an aspect has allowed for developing essentially undamped analyses, reducing computational times without loosing in approach generality and/or underestimating the real response.

2.4 Analysis of results

For the considered door, the analyses have highlighted an elastic response for the internal frame in the peak phase (**Figure 9**), with occurrence of out-of-plane displacements compatible with the correct structural behaviour of the whole door, both in the peak and rebound phase

(**Figure 10**).

Further, constraints reactions (variable with the structure's oscillation consequent to the explosion) have been analysed and maximum values have been taken as reference; in general, internal hinges appeared to be overloaded, due to the door's bending, and their verification has been developed in agreement with Eurocode 3 (**Figure 11**); anchoring bolts of the perimetric counter-frame have been checked as well.

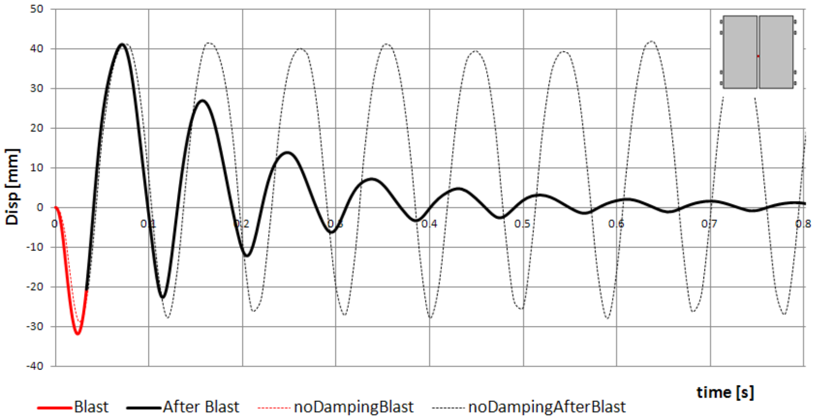

Figure 8: Displacement vs. time for damped and undamped analyses.

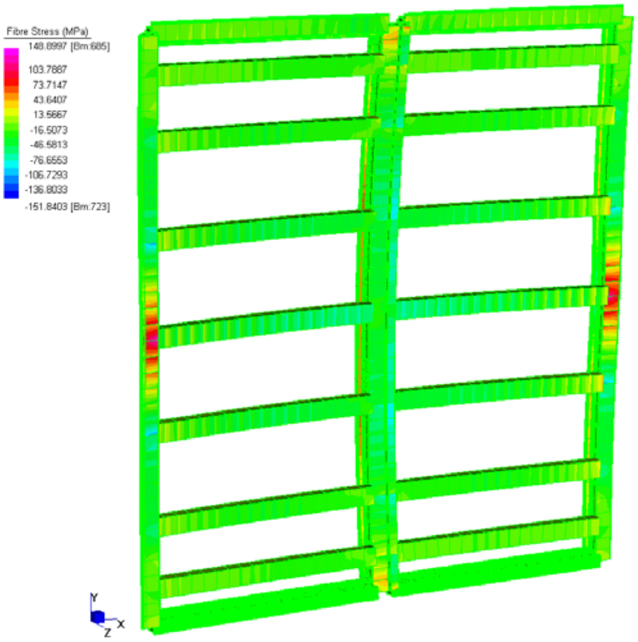

Figure 9: Maximum stresses in the peak phase, internal frame.

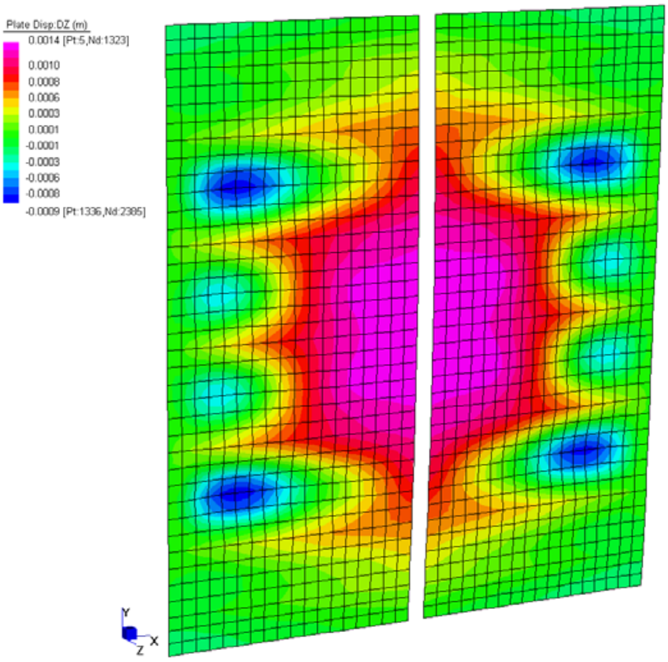

Figure 10: Contour map of out-of-plane displacements during rebound (steel plates).

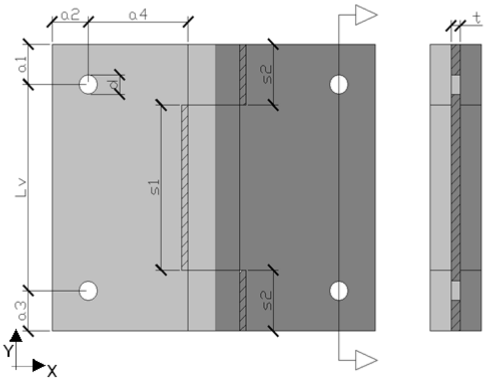

Figure 11: Geometric scheme for hinges' verification.

The design of the door has been then completed via tensile/compressive, bending and shear (and coupled actions) verifications for each structural element following the procedures of the Ultimate Limit States; as required by EC3, design and resistant actions ratios have been controlled to check their being lower than one, both in the peak and rebound phase, as well as close to these states. When such a limit had not been satisfied and correspondingly for some elements a plastic regime had been evidenced, the respect of the additional limits provided by ASCE standards in term of ductility and rotation ratios have been controlled.

3 EXPERIMENTAL TESTS

The results obtained from the numerical analyses in terms of strength and deformability have been subsequently compared with those coming from laboratory tests, conducted on a real scale door, confirming the correctness of approaches and methodologies as well as the door capability to sustain dynamic loads even larger (nearly double) than the design ones. The tests have been developed at the Laboratory of Construction Materials of the Department of Structural and Transportation Engineering in Padua, Italy. Even in an "ultimate" configuration, the requirement of a door reopening has been guaranteed, proving its efficiency in response and technical realization for dynamic regimes.

The test scheme has been planned to (dynamically) reconstruct the explosive event even without using blast-reproducing devices, hence minimizing costs connected to the entire test set-up but anyway ensuring a correspondence between tests and real behaviour. It has consequently been chosen to perform an impacting mass with fixed weight to be thrown against the door; the nature of the impact is so local, being the impact area not distributed on the whole door's surface (**Figure 12**), but such a condition has been verified to be more severe in the evaluation of the door behaviour, so once again ensuring a more precautionary situation.

Figure 12: Test set-up: impacting element (left) and position of displacement transducers (right).

The design condition has been reconstructed making reference to energetic equivalences, by matching the kinetic energy associated to the impacting mass with the work done by the blast load; in this way a "design" height has been determined, such as to certify that the impact could lead to pressure values equivalent to the explosion ones.

Via such an approach it has not been possible to take into account the (real) transient nature of the pressure wave; a possible, consequent, underestimate in the blast effects is however associable to the rebound phase only, but these have been evaluated as negligible: in fact, the maximum displacements used in the energetic equivalence above are numerically derived and consequently they come from having included real quantities such as reflected pressure (higher than the design one) and wave duration. It is additionally verifiable that a structure is more sensitive towards a variation in the peak pressure rather than in a different time distribution of the pressure wave itself.

In the methodological definition of the tests and in the subsequent discussion of results even effects coming from deformable constraints have been included as well (in fact, in the test the door is not restrained to any edge wall).

It has been observed from the displacement values measured by transducers (**Figure 13**) that: a) the whole system response (door and supporting frames) results damped, favorable condition for a structure designed to respond to dynamic loads; b) the peaks in the curve subsequent to the first one are effectively "fictitious" (i.e. non reproducible in reality), because consequent to the repeated impact of the mass and strictly related to the planned tests (it is however possible to say that such a phenomenon represents a condition in favor to safety, being the door more stressed); c) a rebound is evidenced: this could be amplified in reality, due to a depressurization consequent to the explosion, but such an aspect is believed to have no consequences on the real capacity of the door for sustaining loads, nor on its reopening (**Figure 14**).

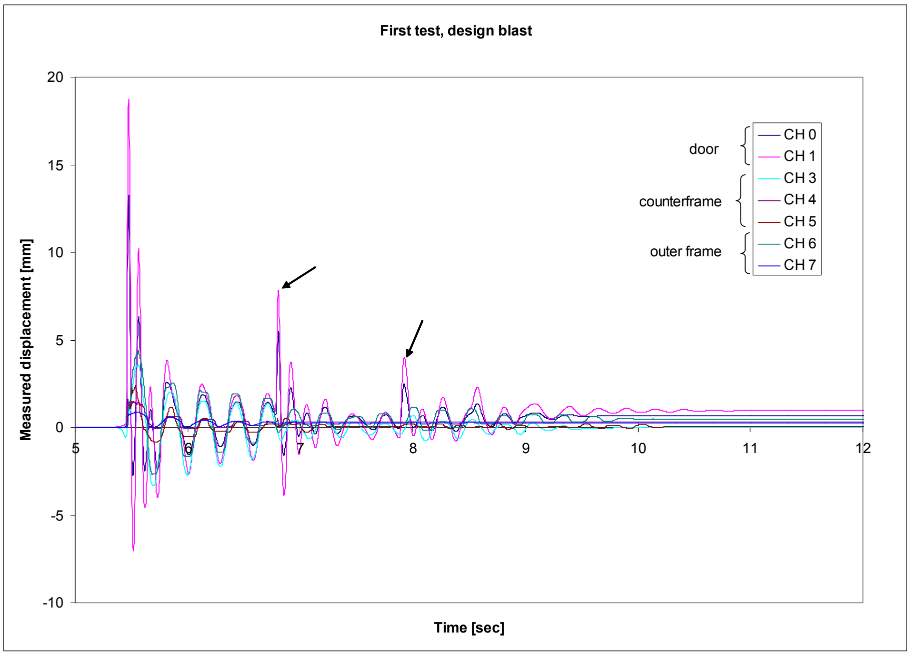

Figure 13: Measured displacements, test with design pressure.

The tests (conducted in 3 subsequent phases), as anticipated, have allowed for demonstrating the validity of the hypotheses and of the adopted procedures, as well as to prove the agreement between numerical and experimental results. Even including (necessary) simplifying assumptions, the tests have shown a correct structural behaviour for the door, both under the design load and for nearly double ones, not only without evidencing collapse phenomena (even locally), but also qualifying the post-explosion functional character of the door itself.

Figure 14: Door reopening after design blast.

4 CONCLUSIONS

Numerical-experimental results have been briefly described, referring to an innovative experience, at both national and international level, in modelling, designing and realizing steel blast-resistant doors and windows.

The study has been conducted to define and characterize the non-linear response of a large number of doors and windows with steel frame, with the objective of sustaining dynamic loads from explosive hazards of fixed magnitude and variable design and clearing times.

The local overcome in the strength limit (i.e. generating a plastic response) and possible formation of plastic hinges has been critically discussed and examined in relation to prescribed Regulations and Recommendations.

The numerical models have allowed for refining first design sketches and subsequently understanding the real structural behaviour of the investigated structures.

Experimental tests on typical steel doors at 1:1 scale have been conducted with the objective of “a-posteriori” verifying the correctness of the already available numerical results, validating the adopted procedures and correspondingly guaranteeing the doors’ structural efficiency even under dynamic loads even higher than design ones. Their capability to sustain thermal loads due to fire hazards has been additionally accounted for.

REFERENCES

[1] ASCE Report. *Design of Blast Resistant Buildings in Petrochemical Facilities*, NY (1997).

[2] UNI EN 1993-1-1. *Eurocode 3: Design of steel structures. Part 1-1: General rules and rules for buildings* (1993 and 2005).

[3] UNI EN 13541:2000. *Glass in building – Security Glazing – Testing and classification of resistance against explosion pressure* (2000).

[4] UNI EN 572-1:2004. *Glass in building - Basic soda lime silicate glass products - Part 1: Definitions and general physical and mechanical properties* (2004).

[5] prEN 13474-2 (CENT/TC129/WG8). *Glass in building - Design of glass panes - Part 2: Design for uniformly distributed loads* (2000).

[6] Majorana C.E., Salomoni V.A. Preliminary design and numerical analyses of steel blast doors and windows, *V Asia-Pacific Conference on Shock and Impact Loads on Structures*. 301-307 (2003) (ISBN: 981-04-8563-8).

[7] Salomoni V.A. Predicted Responses of Structures Subjected to Blast and Blast-Induced Phenomena, *2^ Int. Conf. On Protection of Structures Against Hazards*. Singapore, Dec. 01-03 (2004) (ISBN: 981-05-0613-9).

[8] Naval Facilities Engineering Command. *Blast resistant structures - Design Manual 2.08*. Philadelphia, PA (1986).

[9] BP International Limited, Research & Engineering Centre. *Procedure for the Design of Buildings subject to Blast Loadings. RP 4-6*. BP Group Recommended Practices and Specifications for Engineering: Engineering Practices Group, Chertsey Road, Sunbury-on-Thames, Middlesex, TW16 7LN, UK (1993).