Structural Engineering and Mechanics, *Vol. 60, No. 2 (2016) 211-223*
DOI: http://dx.doi.org/10.12989/sem.2016.60.2.211

Polypropylene fiber reinforced concrete plates under fluid impact. Part I: experiments

Hasan Korucu*[1,2]

[1]*Turkish Armed Forces Headquarters, Department of Engineering, 06100 Bakanliklar, Ankara, Turkey*
[2]*Purdue University, Lyles School of Civil Engineering, West Lafayette, IN 47907, United States*

(Received March 29, 2016, Revised June 15, 2016, Accepted June 16, 2016)

Abstract. Static loading and fluid impact tests on plates containing mesh reinforcement and polypropylene fibers in ratios of 0 to 3% by volume were performed. The objective was to observe the effect of fluid mass on the total impulse that caused the impact event and the influence of fiber amount on the impact resistance, and to estimate the velocity of fluid that causes scabbing, perforation or total disintegration. The study is the first to express the fluid impact resistance of polypropylene fiber reinforced concrete plates.

Keywords: fluid impact; polypropylene fibers; projectile; plate; static loading

1. Introduction

In 1960s, there was a big increase in the number of nuclear power plants in USA. Many of these power plant facilities were built close to commercial or military airports. Safety of these power plants against a possible accidental aircraft crash was of concern.

When a Boeing 707-320 strikes a structure with a fuel weight of almost one-third of its total weight without cargo (28.8 tons/80.3 tons), the effect of fluid impact before combustion becomes the major harmful parameter during impact (Flightglobal 2016). Riera (1968) presented a formulation of a thin-walled cylinder representing an accidental impact of a large commercial aircraft against a rigid surface at a velocity of 200 knots (370 km/s). Sugano *et al*. (1993) carried out an experimental research, impact of a F-4 Phantom with an impact velocity of 215 m/s onto a reinforced target. F-4 Phantom's 4.8 tons of 19 ton- gross-weight was the weight of water. Their aim was to record the dispersal of water, as representative for fuel, after impact.

Fluid-solid interaction is also an important issue in areas like safety of industrial facilities and survivability of wing fuel tanks of aircrafts. This fact was studied both numerically and experimentally by Sauer (2011), Varas *et al*. (2009) and Disimile *et al*. (2009). The hydrodynamic ram, dangerously high pressure created by the energy transfer from an impacting projectile may cause explosion of fuel tank joints, seams or walls that leads to loss of the structure. An aircraft shot by small arms fire or even runway debris, as in the case of Concorde 203 F-BTSC which was crashed after takeoff from Paris, impacted and penetrated the fuel tank and caused hydrodynamic ram resulted by structural failure (Moussa *et al*. 1997).

*Corresponding author, Ph.D., E-mail: korucu_h@yahoo.com

http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

The airplane crashed onto Pentagon Building on September 11, 2001 was a Boeing 757-200, which weighed approximately 82.34 tons, which 16.42 tons was fuel at the time of impact. The impact speed was 460 knots~240 m/s. After the crash, 30 of the columns were missing, broken, disconnected or had significant corruption, 28 of them had large deformation, heavy cracking and spalling, and 26 of them had cracking and spalling but no significant corruption occured (Mlakar *et al*. 2005a, b).

The impact of a Boeing 767-200ER aircraft to World Trade Center I on September 11 was analytically studied performing a finite-element modeling using LS-DYNA. 30 tons of fuel and 98 tons of dry mass of the aircraft were taken into account. SPH elements were used in modeling to simulate fluid-structure interaction during the impact assuming no fire followed by the impact. Impact velocity of the aircraft was 200 m/s. 52 columns of stories between 94 and 99 were heavily damaged or core columns were destroyed. Impact caused a significant damage, but comparing the effect of approximately 700°C temperature, it had a negligible effect in occurrence of instability and initiating collapse of the steel structure (Irfanoglu and Hoffmann 2008). The damage inflicted by aircraft impact on the insulation of the core framing was the dominant factor in the collapse of the structure (Miamis *et al*. 2009). Impact analyses showed that if the aircraft did not have a full fuel tank in the wing section, normal impact on the exterior wall of any of the WTC towers might produce significant damage to the exterior columns but they might not fail at all. For the same impact speed, impact by a fuel-filled aircraft wing section resulted in complete failure of the exterior columns (Sunder 2005).

The collision between fluid-filled container and a structural barrier was studied both experimentally and analytically by Pujol and Brachmann (2007). It was aimed to find out a simple way to estimate the energy transferred to the barrier by the impacting liquid body. Experimental study was performed by using thin aluminum cylindrical containers filled with beer. Maximum projectile velocity was 90 m/s. The results showed that the energy transferred to the barrier could be estimated if $m/M_e << 1$ where m was the mass of the projectile, and M_e was the effective mass of the barrier. As it has been proved that the wings of an airplane filled with fuel may cause heavy damage to a structure, this result was relevant to the design of structures to resist aircraft impact (Sunder 2005, Mlakar 2003). This problem was also previously studied theoretically and numerically by Xue and Wierzbicki (2003). High-speed impact of a liquid-filled cylinder onto a rigid wall was observed. A closed-form solution from the principle of momentum conservation was derived.

Finite element analysis is widely used by researchers to test the accuracy and fidelity of the model built and to confirm the damage in structural impact tests (Micheli *et al*. 2015, Nouri *et al*. 2015, Dancygier 2009, Aghaei *et al*. 2015, Jankowiak *et al*. 2014, Korucu and Gülkan 2011, Mazek and Mostafa 2014).

Great variety of impact tests were carried out using drop-weight impact instruments on concrete specimens containing polypropylene fibers (Mindess and Vondran 1988, Barr and Bourmata 1988, Badr *et al*. 2006, Nia *et al*. 2012, Nili and Afroughsabet 2010, Rahmani *et al*. 2012, Song *et al*. 2005, Manolis *et al*. 1997), polymer (Kantar and Anil 2012), steel fibers (Perumal 2014) or no fibers (May *et al*. 2006).

No research on high-velocity fluid impact on concrete structures containing polypropylene fibers was performed before. In this study, static loading and impact tests on plates containing mesh reinforcement and polypropylene fibers in ratios of 0 to 3% by volume were performed at the Bowen Laboratory for Large-scale Civil Engineering Research of Purdue University. The effect of fluid mass on the impact event was observed and the velocity of fluid that caused

Table 1 Mortar mix proportion

Material	Ratio
Cement : Silica Fume : Superplasticizer	28.2 : 1 : 0.45
Water/Cement	0.32
Polypropylene Fibers	0 %, 1 %, 2 %, 3% by volume

Fig. 1 Polypropylene fibers

scabbing, perforation or total disintegration was estimated. The study is the first to express the fluid impact resistance of polypropylene fiber reinforced concrete plates. All the impact tests were also modeled and simulated using LS-DYNA software and the results are presented in the companion Part II of this study (Korucu 201X).

2. Preparation of specimens

For the experimental study, 20 fiber reinforced concrete plates were fabricated. These plates were classified in four groups and each group had five identical plates, 254 mm in length and width, and 25 mm in thickness. The reinforcement used in the plates was U.S. No. 16 gage steel wires where the $\phi 16$ wire had a diameter of 1.6 mm. It was configured as $14\phi 16$ both in horizontal and vertical directions with 18 mm spacing. Reinforcement ratio, ρ, was 0.0043. One specimen in each group was subjected to static loading and the rest was impacted by fluid-filled cans. Compression and tensile material tests were performed using six cylindrical specimens, 203 mm in length and 102 mm in diameter, containing fiber amount equal to that in the corresponding plates. Coarse aggregate was not used in the mixture because of dense placement of wires and fibers. All the plates were cast using the same type and proportions of mortar. Mortar mix proportion is given in Table 1. The specimens in the first group did not include any fibers as 1%, 2% and 3% of fibers by volume added into the mortar in three groups, respectively. The polypropylene fibers used in fabrication of specimens were BASF MasterFiber F70, fibrillated microsynthetic fiber. The fibers were manufactured from 100% virgin homopolymer polypropylene resins. The product meets the

Table 2 Physical properties of polypropylene fibers (BASF 2015)

Specific gravity	0.91
Modulus of elasticity	$5.38.10^4$ MPa
Tensile strength	300 MPa
Water absorption	Nil
Percent elongation	13.1%
Length	19 mm
Equivalent diameter	0.66 mm

Fig. 2 Thin-walled cylindrical container

Table 3 Mechanical properties of ϕ16 wire

Yield Stress (MPa)	Young's Modulus (MPa)	Poisson's Ratio	Mass Density (kg/m^3)
275.79	2.10^5	0.3	7850

requirements of ASTM C 1116/C 1116M (BASF 2015). The fibers are shown in Fig. 1 and physical properties are listed in Table 2.

Plates were casted using foam-board forms. The fresh concrete had been cured under 20±5°C temperature and 95% of humidity for a week. Thin-walled cylindrical container is shown in Fig.2. The mechanical properties of the wire are given in Table 3.

3. Experimental procedure

The experimental program was performed in three stages: material tests, static tests and impact tests, in Bowen Laboratory of Purdue University. In each group, the first specimen was tested statically and the rest four was subjected to fluid impact.

Table 4 Results of compression and splitting tests

Group No	Compressive Strength (MPa)	Tensile Strength (MPa)
1	35.70	1.80
	33.27	1.75
	30.80	2.11
2	36.83	4.20
	37.77	4.06
	32.07	4.30
3	36.18	4.50
	31.54	4.82
	38.56	4.85
4	31.70	5.23
	36.48	5.14
	35.76	4.99

Fig. 3 The static test setup

3.1 Material tests

Six cylindrical specimens, 203 mm in length and 102 mm in diameter, were produced during casting of concrete to determine the compressive and tensile strength of the concrete. Half of these specimens were subjected to compression while the other half was tested in tension on the day of impact tests. The specimens were formed by adding same amount of fibers as in the plates in each group.

Both compression and splitting tests were carried out using a 2670 kN testing machine with a resolution of 0.45 kN. The loading rate applied was 13.8 MPa/min for compression and 0.7 MPa/min for splitting tests. The test results are listed in Table 4.

3.2 Static tests

In order to obtain the flexural capacity of the plates, a distributed load at the mid-span line was subjected to the mid-span of the beams by a 22.24 kN load cell fixed to a gear jack which is shown in Figs. 3 and 5. The deflections were measured using linear variable differential transformers (LVDTs) which were located at the rear of the mid-span and quarter points of the plates. Plates

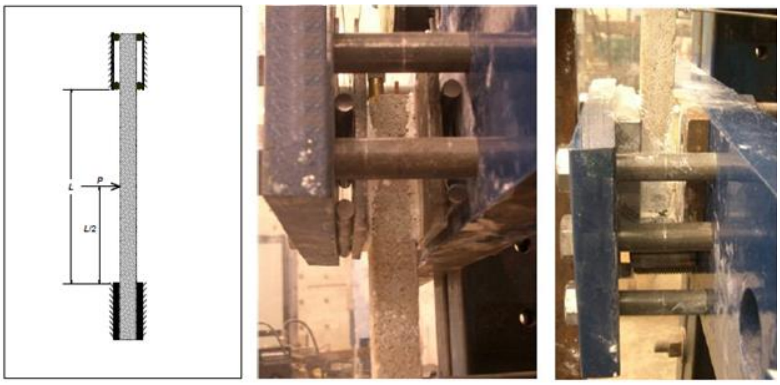


Fig. 4 Support conditions

(a) Post-test view of (a) P 1-1

(b) Post-test view of (a) P 2-1

(c) Post-test view of (a) P 3-1

(d) Post-test view of (a) P 4-1

Fig. 5 Static test results

were restrained against rotation along the top and bottom edges. The static test setup and support conditions are shown in Figs. 3-4. Post-test views of statically loaded plates from both sides are shown in Fig. 5. Load-displacement curves obtained at the mid-span are given in Fig. 6.

Higher fiber ratio improved the flexural strength of the plates as shown in Fig. 6. Specimen P 4-1 consisting 3% of fiber, had almost double the load capacity of P 1-1 specimen without fiber.

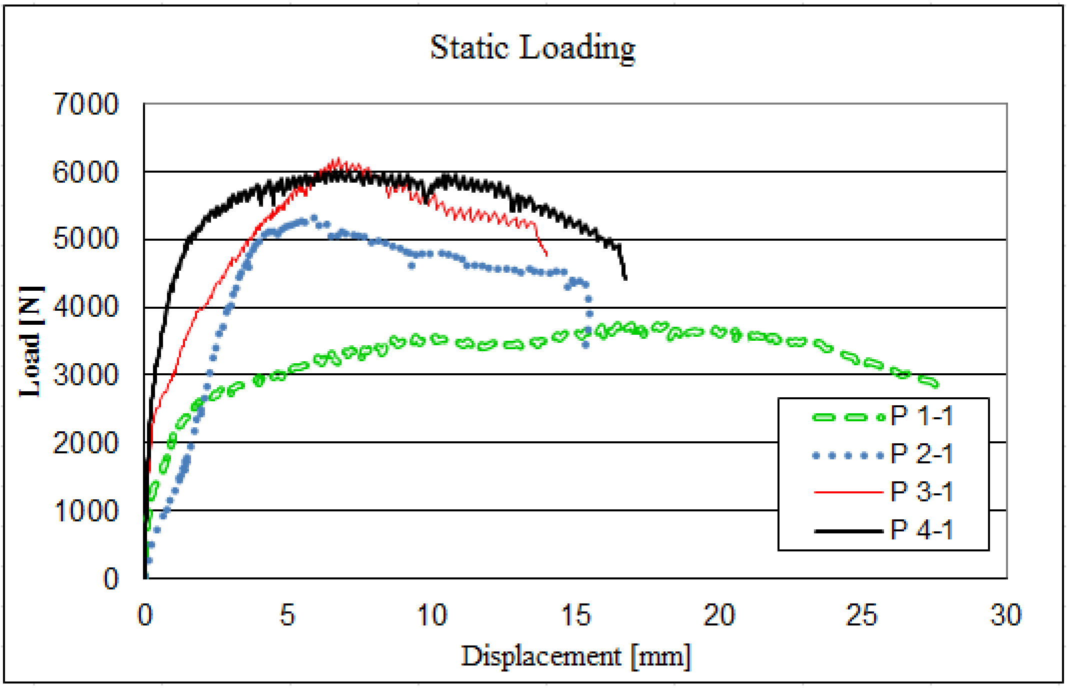


Fig. 6 Load-displacement curves obtained from static tests

Table 5 Mechanical properties of aluminum

Yield Stress (MPa)	Young's Modulus (MPa)	Poisson's Ratio	Mass Density (kg/m^3)
275	6.9.10^4	0.3	2750

3.3 Impact tests

In each group, four specimens were subjected to impact tests. Impacting projectiles were thin-walled aluminum containers filled with water. These cylindrical containers had a length of 95 mm and a diameter of 51 mm, and wall thickness of 0.05 mm. The average weight of the water in the container was 185 g and the weight of the container was 9 g. The mechanical properties of the aluminum are given in Table 5.

A helium gas gun was used as a launcher to accelerate the aluminum containers full of water to the middle of plates. Support conditions were identical to those in static tests. In order to observe the effects of different impact forces on the plates, the impact velocity was changed in each test. LVDTs were not used because they deformed excessively and did not give reliable results due to high impact velocity. Instead, impact event, crack formation and deformation were observed using a high-speed camera which was capable of recording up to 250.000 frames per second. The high-speed camera and laser triggered photo detectors were used to measure the impact velocity. As more reliable results were obtained by the laser triggered photo detectors, estimates from them were accepted as impact velocity where available. The test setup is shown in Fig. 7.

The weight of projectile, the impact velocities measured by camera and the laser triggered photo detectors and the post-impact states observed are given in Table 6. The deformed shapes

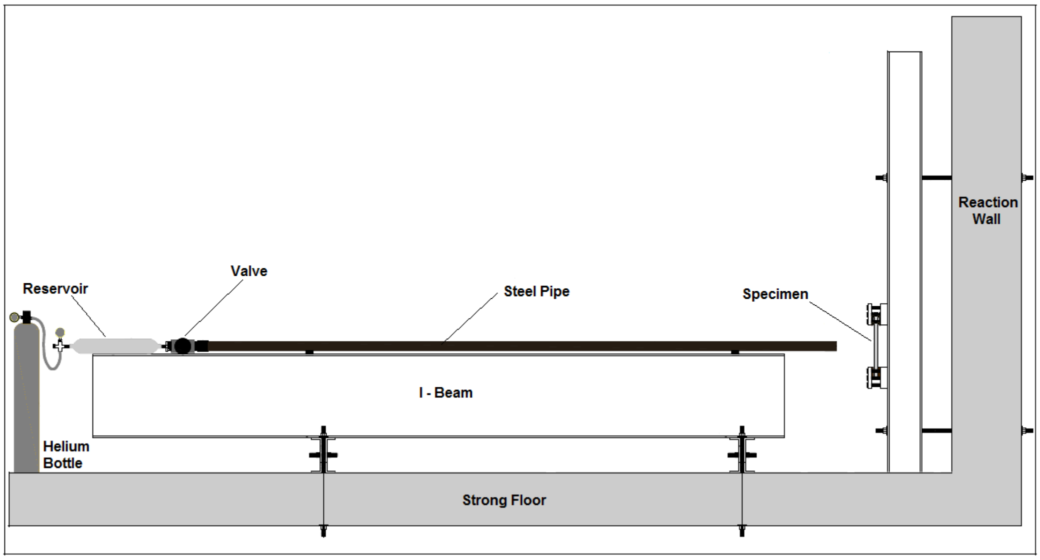


Fig. 7 The impact test setup

Table 6 Weight of projectile, impact velocities and post-impact states

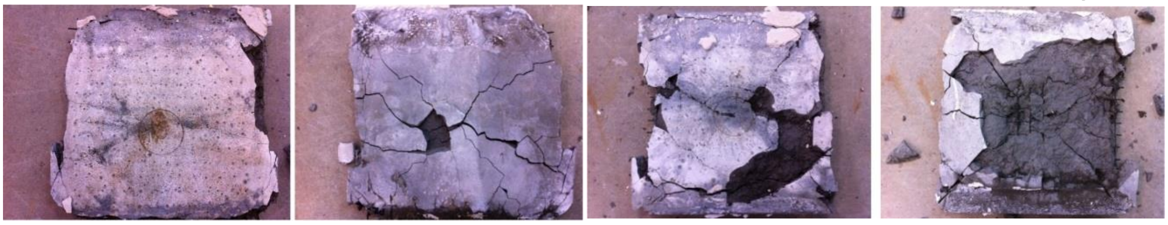
No.	Weight of Projectile (g)	Impact Velocity (m/s)		Post-Impact State
		Camera	Laser	
P 1-2	188	107	101	Scabbing
P 1-3	193	135	132	Perforation and total disintegration
P 1-4	182	76	74	Scabbing
P 1-5	186	99	94	Scabbing
P 2-2	185	78	70	Scabbing
P 2-3	179	141	136	Perforation with scabbing
P 2-4	182	98	97	Scabbing
P 2-5	188	133	130	Scabbing
P 3-2	191	138	136	Penetration with scabbing
P 3-3	191	171	167	Penetration with scabbing
P 3-4	193	203	207	Perforation with scabbing
P 3-5	190	196	190	Perforation with scabbing
P 4-2	190	123	125	Penetration with scabbing
P 4-3	191	163	N/A	Perforation and total disintegration
P 4-4	190	165	161	Perforation with scabbing
P 4-5	193	N/A	183	Perforation with scabbing

obtained after impact event are shown in Figs. 8-11.

Taking a look at the compatibility of deformations and impact velocities as expected, higher impact velocity always caused greater deformation on the specimens in each group.

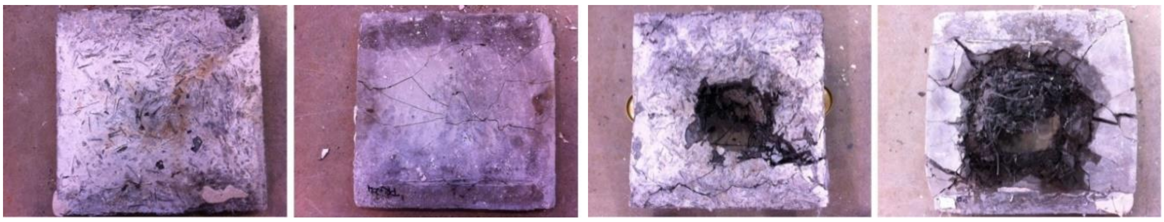
Approximate perforation impact speed ranges for each group of specimens are given in Table 7.

(a) P 1-2 (b) P 1-3 (side-view shown because of disintegration)



(c) P 1-4 (d) P 1-5

Fig. 8 Impact test results: Post-test views for front and rear sides



(a) P 2-2 (b) P 2-3

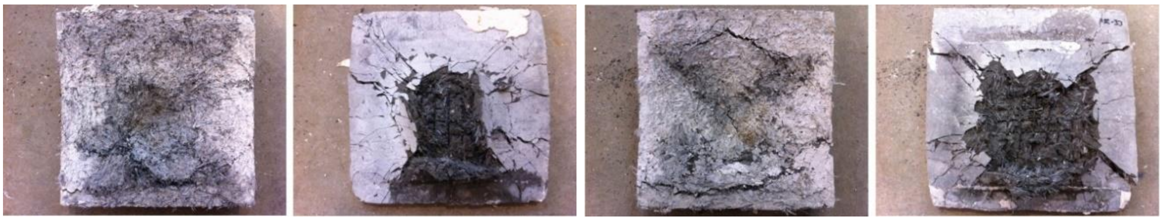
(c) P 2-4 (d) P 2-5

Fig. 9 Impact test results: Post-test views for front and rear sides

Perforation impact speed ranges show that increase in the fiber ratio increased the perforation resistance of specimens except for Group 4. In Group 4, the higher fiber ratio of 3% was beyond the optimum and caused a decrease in the strength.

Experiments also showed that the reinforcement wires were the significant members in the specimens resisting the fluid impact. It was observed that wires showed a great performance resisting the impact and even concrete was totally disintegrated, the wire mesh was only deformed, not corrupted. It was observed that some reinforcing wires were pulled from connection points in specimens subjected to higher impact velocities without fracture indicating that bond failure occurred.

Comparing the disintegration type of P 1-3 where there was no fiber with other specimens in Groups 2, 3 and 4, the effect of the polypropylene fibers can be seen clearly. Fibers prevented



(a) P 3-2 (b) P 3-3

(c) P 3-4 (d) P 3-5

Fig. 10 Impact test results: Post-test views for front and rear sides

(a) P 4-2 (b) P 4-3

(c) P 4-4 (d) P 4-5

Fig. 11 Impact test results: Post-test views for front and rear sides

Table 7 Perforation speed ranges

Group	Fiber Ratio (%)	Speed Range (m/s)
1	0	101-132
2	1	130-136
3	2	167-190
4	3	125-161

disintegration and spalling significantly. Polypropylene fibers increased the tensile and shear strength of concrete, especially where wires did not exist, and acted as a secondary reinforcement.

4. Conclusions

Impact tests were performed to observe the effect of fluid mass on the total impulse that caused the impact event on the plates containing polypropylene fibers and impact velocity of the projectile in the failure mechanism. Plates showed better performance at low velocities, crushing developed but perforation was avoided. At higher impact velocities full deformation, disintegration and spalling were observed especially in specimens without polypropylene fibers. In static tests, all the plates subjected failed in flexure.

Approximate minimum speed ranges were determined. The perforation speed increased as amount of fibers increased from none to 1% by volume and 2% by volume. However penetration speed for Group 4 showed a dramatic decrease. The reason for this behavior was interpreted as 3% of fiber ratio was beyond the optimum.

Fibers helped avoiding total disintegration and the size of the scabbed area on the rear face decreased with the increase in fiber ratio.

Reinforcing wires had positive effect in resisting the high value tensile and shear stresses which come up with develop during impact loading**.**

Acknowledgements

The author acknowledges Prof. Mete A. Sozen and Assoc.Prof. Ayhan Irfanoglu for their supervision during period of the study, and Prof. Santiago Pujol, Harry Tidrick, Kevin Brower, Pedram Khajeshhesameddin who did not hesitate to share their knowledge and contribution to the work, and BASF Chemical Company for providing the fibers.

This research was carried out with the support of TUBITAK (The Scientific and Technological Research Council of Turkey) to the author as a post-doctoral scholarship.

Disclaimer

The commercial products named in this article are intended only for description of the experimental environment and do not necessarily imply their endorsement or approval by the author or any other party.

References

Aghaei, M., Forouzan, M.R., Nikforouz, M. and Shahabi, E. (2015), “A study on different failure criteria to predict damage in glass/polyester composite beams under low velocity impact”, *Steel Compos. Struct.*, **18**(5), 1291-1303.

Badr, A., Ashour, A.F. and Platten, A.K. (2006), “Statistical variations in impact resistance of polypropylene fibre-reinforced concrete”, *Int. J. Impact Eng.*, **32**(11), 1907-1920.

Barr, B. and Bouamrata, A. (1988), “Development of a repeated drop-weight impact testing apparatus for studying fibre reinforced concrete materials”, *Compos.*, **19**(6), 453-466.

BASF Chemical Company (2015), Available from: http://www.master- builders-solutions.basf.us/en/us/ products/masterfiber/1651?Product= MasterFiberF70., Construction Chemicals, Beachwood, OH, USA.

Cheng, X., Zhao, W., Liu, S., Xu, Y. and Bao, J. (2014), “Damage of scarf-repaired composite laminates subjected to low-velocity impacts", *Steel Compos. Struct.*, **17**(2), 199-213.

Dancygier, A.N. (2009), "Characteristics of high performance reinforced concrete barriers that resist non-deforming projectile impact", *Struct. Eng. Mech.*, **32**(5), 685-699.

Disimile, P.J., Luke, A.S. and Toy, N. (2009), "The hydrodynamic ram pressure generated by spherical projectiles", *Int. J. Impact Eng.*, **36**(6), 821-829.

Flightglobal (2016), Available from: https://www.flightglobal.com/pdfarchive/view/1958/1958-1-%20-%200145.html,Quadrant House, The Quadrant, Sutton SM2 5AS, UK.

Irfanoglu, A. and Hoffmann, C.M. (2008), "Engineering perspective of the collapse of WTC-I", *J. Perform. Constr. Fac.*, **22**(1), 62-67.

Jankowiak, T., Rusinek, A., Kpenyigba, K.M. and Pesci, R. (2014), "Ballistic behavior of steel sheet subjected to impact and perforation", *Steel Compos. Struct.*, **16**(6), 595-609.

Kantar, E. and Anil, O. (2012), "Low velocity impact behavior of concrete beam strengthened with CFRP strip", *Steel Compos. Struct.*, **12**(3), 207-230.

Korucu, H. (2016), "Polypropylene fiber reinforced concrete plates under high velocity fluid impact. Part II: modeling and simulation", *Struct. Eng. Mech.*, **60**(2), 225-235

Korucu, H. and Gülkan, P. (2011), "High-velocity impact of large caliber tungsten projectiles on ordinary Portland and calcium aluminate cement based HPSFRC and SIFCON slabs. Part I: experimental investigations", *Struct. Eng. Mech.*, **40**, 595-616.

Manolis, G.D., Gareis, P.J., Tsonos, A.D. and Neal, J.A. (1997), "Dynamic properties of polypropylene fiber-reinforced concrete slabs", *Cement Concrete Compos.*, **19**(4), 341-349.

May, I.M., Chen, Y., Owen, D.R.J., Feng, Y.T. and Thiele, P.J. (2006), "Reinforced concrete beams under drop-weight impact loads", *Comput. Concrete*, **3**(2), 79-90.

Mazek, S.A. and Mostafa, A.A., "Impact of composite materials on performance of reinforced concrete panels" *Comput. Concrete*, **14**(6), 767-783.

Miamis, K., Irfanoglu, A. and Sozen, M.A. (2009), "Dominant factor in the collapse of WTC-I", *J. Perform. Constr. Fac.*, **23**(4), 203-208.

Micheli, G.B., Driemeier, L. and Alves, M. (2015), "A finite element-experimental study of the impact of spheres on aluminium thin plates", *Struct. Eng. Mech.*, **55**(2), 263-280.

Mindess, S. and Vondran, G. (1998), "Properties of concrete reinforced with fibrillated polypropylene fibres under impact loading", *Cement Concrete Res.*, **19**(1), 109-115.

Mlakar, P.F., Dusenberry, D.O., Harris, J.R., Haynes, G., Phan, L.T. and Sozen, M.A. (2005a), "September 11, 2001, airliner crash into the Pentagon", *J. Perform. Constr. Fac.*, **19**(3), 189-196.

Mlakar, P.F., Dusenberry, D.O., Harris, J.R., Haynes, G., Phan, L.T. and Sozen, M.A. (2005b), "Description of structural damage caused by the terrorist attack on the Pentagon", *J. Perform. Constr. Fac.*, **19**(3), 197-205.

Mlakar, P.F., Dusenberry, D.O., Harris, J.R., Haynes, G., Phan, L.T. and Sozen, M.A. (2003), "The Pentagon building performance report", ASCE Structural Engineering Institute, Reston, VA, USA.

Moussa, N.A., Whale, M.D., Groszmann, D.E. and Zhang, X.J. (1997), "The potential for fuel tank fire and hydrodynamic ram from uncontained aircraft engine debris", Final Report., Report No.: DOT/FAA/AR-96/95, Department of Transportation (US), Federal Aviation Administration, Washington D.C., USA.

Nia, A.A., Hedayatian, M., Nili, M. and Sabet, V.A. (2012), "An experimental and numerical study on how steel and polypropylene fibers affect the impact resistance in fiber-reinforced concrete", *Int. J. Impact Eng*., **46**, 62-73.

Nili, M. and Afroughsabet, V. (2010), "The effects of silica fume and polypropylene fibers on the impact resistance and mechanical properties of concrete", *Constr. Build. Mater.*, **24**(6), 927-933.

Nouri, M.D., Hatami, H. and Jahromi, A.G. (2015), "Experimental and numerical investigation of expanded metal tube absorber under axial impact loading", *Struct. Eng. Mech.*, **54**(6), 1245-1266.

Perumal, R. (2014), "Performance and modeling of high-performance steel fiber reinforced concrete under impact loads", *Comput. Concrete*, **13**(2), 255-270.

Pujol, S. and Brachmann, I. (2007), "Experimental and analytical study on the response of barriers to fluid impact. Technical report", Civil Engineering, Purdue University, West Lafayette, IN, USA.

Rahmani, T., Kiani, B., Shekarchi, M. and Safari, A. (2012), "Statistical and experimental analysis on the behavior of fiber reinforced concretes subjected to drop weight test", *Constr. Build. Mater.*, **37**, 360-369.

Riera, J.D. (1968), "On stress analysis of structures subjected to aircraft impact forces", *Nucl. Eng. Des.* **8**(4), 415-426.

Sauer, M. (2011), "Simulation of high velocity impact in fluid-filled containers using finite elements with adaptive coupling to smoothed particle hydrodynamics", *Int. J. Impact Eng.*, **38**(6), 511-520.

Song, P.S., Hwang, S. and Sheu, B.C. (2005), "Strength of nylon and polypropylene fiber reinforced concretes", *Cement Concrete Res.*, **35**(8), 1546-1550.

Sugano, T., Tsubota, H., Kasai, Y., Koshika, N., Orui, S., von Riesemann, W.A., Bickel, D.C. and Parks, M.B. (1993), "Full-scale aircraft impact test for evaluation of impact force", *Nucl. Eng. Des.*, **140**(3), 373-385.

Sunder, S.S. (2005), Federal building and fire safety investigation of the World Trade Center Disaster: Final report of the National Construction Safety Team on the collapses of the World Trade Center Towers, Final report., Report No.: NIST NCSTAR 1, National Institute of Standards and Technology (NIST) Gaithersburg, MA, USA.

Varas, D., Lopez-Punte, J. and Zaera, R. (2009), "Experimental analysis of fluid-filled tubes subjected to high-velocity impact", *Int. J. Impact Eng*., **36**(1), 81-89.

Xue, L. and Wierzbicki, T. (2003), "High-speed impact of liquid-filled cylinders", Report No.:108, MIT, Impact and Crashworthiness Laboratory, Cambridge, MA, USA.

PL