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Soft impact testing of a wall-floor-wall reinforced concrete structure

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HIGHLIGHTS

- A wall-floor-wall reinforced concrete structure was built.
- The structure was subjected to three almost identical soft impact tests.
- Response was measured with accelerometers, displacement sensors and strain gauges.
- Modal tests was also carried out with the same structure in different conditions.
- The results are meant to be used for validation of computational methods and models.

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ABSTRACT

Assessing the safety of the reactor building of a nuclear power plant against the crash of an airplane calls for valid computational tools such as finite element models and material constitutive models. Validation of such tools and models in turn calls for reliable and relevant experimental data. The problem is that such data is scarcely available. One of the aspects of such a crash is vibrations that are generated by the impact. These vibrations tend to propagate from the impact point to the internal parts of the building. If strong enough, these vibrations may cause malfunction of the safety-critical equipment inside the building. To enable validation of computational models for this type of behaviour, we have conducted a series of three tests with a wall-floor-wall reinforced concrete structure under soft impact loading. The response of the structure was measured with accelerometers, displacement sensors and strain gauges. In addition to impact tests, the structure was subjected to modal tests under different conditions. The tests yielded a wealth of useful data for validation of computational models and better understanding about shock induced vibration physics especially in reinforced concrete structures.

1. Introduction

A possible accidental crash of an airplane has been long considered as one of the design bases for nuclear power plants (NPP). The planes used for the postulated crashes have been rather small when compared to the largest modern passenger planes, such as Airbus 380 and Boeing 747-8. The 9/11 terrorist attacks showed the world that even deliberate large passenger aircraft crashes are possible. This event rightfully raised a question of whether existing plants can resist such a crash and how safeguarding from this type of beyond-design aircraft impacts should be taken into account when designing and building new plants.

Crashworthiness of NPP structures is obviously demonstrated with numerical computation models and/or empirical, semi-empirical or analytical formulas. The phenomena arising in these crashes are numerous and complicated. The force the structure is subjected to by the impact is obviously very large and can cause large deformations. This might cause yielding and ultimately rupturing of the reinforcement bars and local loss of resistance of the structure. The semi-hard parts of an airplane, like the motors and landing gear, may perforate the structure and cause large amounts of concrete to scab off at the rear surface of the structure. The fuel tanks and the fuel inside them increase the loading. The fuel could then burst out of the tanks and burn, both as an initial fireball and then after flowing along the impacted structure and being collected within lower parts inside and/or outside the structure. In a worst-case scenario, part of the fuel could enter the impacted building and burn inside it. The impact would also generate vibrations, which are likely to propagate from the impacted point towards the internal parts of the building. If strong enough, these vibrations could cause malfunction of the safety-critical equipment

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inside the building, possibly hindering the safe shutdown of the reactor.

In addition to numerous phenomena to be taken into account and reinforced and pre-stressed concrete, the material that the NPP civil structures are most commonly made of, is not the easiest to model. Consequently, modelling of these impacts is by no means an easy task and calls for considerable skills from the modeller(s) as well as reliable modelling tools and models. Experimental data obtained from tests in which similar phenomena arise is invaluable for education of the modeller(s) as well as for validation of the modelling tools and methods. For hard, punching type impact tests, such data can be found in the literature but for the other types of tests, this type of data is scarcely available.

Availability of punching type test results in the literature can be mainly accredited to the high relevancy of the subject in military applications. Owing to this background, the existing data consists mainly of a test series where the ratio between the cross-sectional size of the impacting projectile to the thickness of the impacted target is quite small compared to the corresponding ratio relevant for aircraft crash purposes. A good overview of the topic of hard projectile impacts against concrete targets is given in the work by Li et al. (2005). Similar work has been carried out more recently for example by Kosteski et al. (2015).

Tsugano et al. carried out extensive test series with deformable and rigid projectiles and real aircraft engines to study local effects of the impacts on reinforced concrete slabs (1993a, 1993b). In addition, they executed a real scale test with an F4-Phantom fighter plane that was impacted against a rigid concrete block with dimensions of 7 * 7 * 3.66 m (Tsugano et al., 1993c). The impact velocity in this test was 215 m/s and the main purpose of the test was to verify the so-called "Riera approach", where one can estimate the impact force as a function of time in an impact by a deformable projectile against a rigid target (Riera, 1968).

The so-called Meppen Slab Tests might be the best-known soft impact tests carried out so far (Jonas et al., 1979; Nachtsheim and Stangenberg, 1982, 1983; Rudiger and Riech, 1983). These soft impacts are the ones in which the impacting projectile is considered to be much more deformable than the structure it collides against, simulating the impact of an aircraft fuselage. The Meppen Tests were carried out in Germany near a town called Meppen between 1976 and 1982. These tests mainly concentrated on impacts against vertically oriented square slabs with empty deformable projectiles. The characteristic dimensions of the target slabs were mostly 6 * 6.5 * 0.7 m with the impacting projectile weighing around 1000 kg and having an impact velocity around 200 m/s.

In OECD NEA CAPS IRIS_2010 benchmark (OECD/NEA, 2012; Vepsä et al., 2012), two identical soft and three identical hard impact tests were carried out with 2.1 * 2.1 m simply supported square slabs with thicknesses of 150 and 250 mm. The projectile masses and impact velocities were 50.5 kg and 110–112 m/s for the soft and 47.5 kg and 135–137 m/s for the hard impact tests. The results were used for "blind" prediction benchmark studies and published after the participants of the benchmark had submitted their calculated predictive results for the tests.

VTT Technical Research Centre of Finland has carried out several impact testing projects, concentrating on different aspects of an airplane crash against reinforced concrete structures. These tests have been jointly funded and designed with numerous foreign and domestic partners and carried out by VTT with its test bed. In addition to the soft impact tests (Tarallo et al., 2007), these VTT tests have included tests with water filled projectiles, which simulate the fuel tanks of an aircraft with fuel inside them (Silde et al., 2011; Heckötter and Vepsä, 2015; Hostikka et al., 2015), hard impact tests (Galan and Orbovic, 2015; Orbovic and Blahoianu, 2011; Orbovic et al., 2015; Oliveira et al., 2011.) and tests which combine both bending type failure of soft impacts and punching type failure of hard impacts (Borgerhoff et al., 2013, 2015; Saarenheimo et al., 2015).

Theoretical studies on the harmful effects of airplane impact induced vibration on NPP equipment have been documented since the 1970s. In one of the earliest, if not the earliest, work, Schalk and Wölfel (1976) used simple mathematical models to study the effects of different parameters on floor response spectra induced by such an impact. This floor response spectrum can be defined as the peak response (acceleration, velocity, displacement) of all possible linear single degree of freedom systems to a particular component of ground motion for a given level of damping. The parameters studied in the study of Schalk and Wölfel included the point, direction and eccentricity of the postulated impact, the type of the impacted structure (a cylindrical reactor building versus a rectangular auxiliary building), the stiffness of the soil beneath the structure, the location of the studied point, the local vibrations at the point of impact and the damping of the equipment. Wolf et al. (1978) carried out a similar study, which also included the effects of the modelling method on the loading. Taking into account the date of publishing, Zimmermann et al. (1981) conducted a computationally impressive, but spatially limited study of the influence of material nonlinearities on equipment response spectra. The subject of airplane impact induced floor response spectra was also investigated in the work by Kamil et al. (1978). All the aforementioned papers were published between 1976 and 1980. Since that time, computerized structural analysis capabilities have dramatically increased due to both less expensive and more effective computers and sophisticated finite element method-based software. More recently, the topic of aircraft crashes that include floor response spectra has been numerically studied, for example, by Arros and Doumbalski (2007) and Andonov et al. (2010).

The following points were addressed in the studies mentioned in the previous paragraph:

- A typical response spectrum resulting from an aircraft impact is more dominant in the high-frequency range when compared to a safe-shutdown earthquake. This requires more detailed modelling of higher natural vibration mode shapes of the impacted structure than what is required for an earthquake response analysis.
- Local non-linearities around the hit point do not necessarily reduce the floor response spectra compared to the case of linear analysis. In some cases, it actually magnifies them. This means that models that do not consider non-linear effects at the proximity of the impact point do not necessarily give conservative results.
- If the actual aircraft impact is represented in the computation model by an equivalent, idealized force – time relationship by using the so-called "Riera approach" (decoupled analysis) (Riera, 1968), care must be taken to assure adequate frequency content of the loading. Otherwise, the resulting response spectra will be lacking higher frequency content present in the actual impact. On the other hand, it has been questioned how important this higher frequency content is, in terms of harmfulness to the equipment as the corresponding displacements may well be rather small.

While test data exists on rather local effects of airplane type impacts, tests that simulate impact induced vibration propagation in reinforced concrete structures seem to be non-existent. This led VTT to design a series of soft impact tests with a structure having an impacted wall, a floor and a rear wall, roughly simulating an NPP reactor building with a separate protective shell for aircraft impacts. The tests were carried out by VTT within one of the afore-