



PROPOSAL FOR IMPROVEMENT OF AIRPLANE CRASH AND IMPACT RESISTANCE DESIGN PROVISIONS IN RCC-CW CODE

**Sara Ghadimi Khasraghy¹, François Tarallo², Tadeusz Szczesiak¹, Peter Rangelow³,
Pekka Välikangas⁴, Nicolas Pfeiffer²**

¹ Swiss Federal Nuclear Safety Inspectorate ENSI, Brugg, Switzerland (Sara.Ghadimi@ensi.ch)

² Institut de Radioprotection et de Sûreté Nucléaire IRSN, Fontenay-aux-Roses, France

³ Basler & Hofmann AG, Consulting Engineers, Zurich, Switzerland

⁴ Radiation and Nuclear Safety Authority (STUK), Helsinki, Finland

ABSTRACT

The European Committee for Standardization (CEN) provides a platform for the development of European Standards and other technical documents. CEN Workshops aim to develop best-practice recommendations in specific technical areas. They provide experts with a platform for in depth technical exchange with competent international partners and allow their active contribution to European Standards.

Specific standards and codes provide engineers with essential tools for the design and construction of nuclear structures, systems, and components (SSC). The European nuclear power plants are designed on the basis of different national and international codes and there is a need for harmonization of the design codes in Europe. Therefore, the tentative European adoption of the AFCEN codes was initiated in 2011 with the CEN Workshop on “Design and construction codes for mechanical equipment of innovative nuclear installations” (CEN/WS 64). In “Phase 3” of this workshop, which was completed in 2022, the prospective group PG3 focused on the evaluation of the RCC-CW code, meaning “Règles de Conception et de Construction” (RCC) and “Civil Works” (CW). Among other topics, the airplane crash (APC) and impact related design of the structures was discussed in detail by the PG3 members. This paper presents some of the “Code Evolution” (CE) proposals submitted after the phase 3 to make recommendations for the APC and impact resistance design provisions in the RCC-CW code.

The proposed CEs can improve the consistency of the code and its user-friendliness. This will allow easier application of the design methods, which can significantly help the designers to achieve the robust & safe design of the nuclear SSCs. Additionally, it will assist the regulators in their reviews of such problems. The new proposed provisions for nonlinear impact analysis are currently not extensively included in the available design codes and could be very valuable for the engineers in their decision making and choices for carrying out such complex analyses. This paper discusses the improvement of some of the APC-related issues in the RCC-CW code.

INTRODUCTION

The APC and impact related design of the NPPs and their SSCs is a complex topic. It requires deep technical background and experience to deal with such problems. Currently the topic is addressed in a few nuclear design codes and guidelines such as IAEA 87 Safety Report (2018), HSK-R-102/d (1986), RSK (1981), RCC-CW (2018) and NEI 07-13 (2011), endorsed by NRC (2011). However, the provisions with respect to the APC and impact related design in most of these documents are rather brief and have some shortcomings. Specially, some topics such as nonlinear impact analysis, which can be considered the-state-of-the-art are not extensively covered.

The Prospective Group 3 (PG3) of the CEN/WS 64 Phase 3 focused on support of AFCEN’s development of RCC-CW code towards a common European code. The code (2018 edition) was studied,

reviewed, and discussed by the group members in regular meetings with representatives of AFCEN. In this regards the group provided some code evolution and research proposals. The proposals were then sent to AFCEN according to CEN WS064 procedure. A main topic of discussion by PG3 was APC and impact related design, which focused on improvement of the current provisions in the code.

PROPOSED IMPROVEMENTS

Within the framework of the PG3 of the CEN/WS 64 Phase 3, some code evolution proposals have been made for the RCC-CW code regarding APC and other impact design criteria. These proposals were then submitted to AFCEN for review in the framework of its specialised subcommittees and evaluation of the feasibility of their being taken into account in the codes. On this basis, AFCEN provided a formal answer to the Workshop on its recommendations. Some of these proposals are discussed in the following chapters, providing the summary of the submitted CEs after phase 3.

Simplified Structural Response Analysis

The appendix DC of the RCC-CW code provides a methodology based on a lumped-mass-spring model for structural impact analysis on the basis of the CEB-187 (1988) model. According to the code a simplification of this method is considered for a conservative check of the punching resistance under soft or hard impact. (AN: appendix DC also provides a punching resistance, adapted from appendix DH for impact cases, to be used for soft impacts and assessment of a punching ratio. This latter method is not dealt with in the following).

The simplified impact analysis is performed by checking the energy balance of the punching cone formed in a reinforced concrete slab (or wall) under impact loading. However, currently two formulae in the RCC-CW code (in sections DC 4140 and DC 6000) aim to verify this energy balance using different considerations.

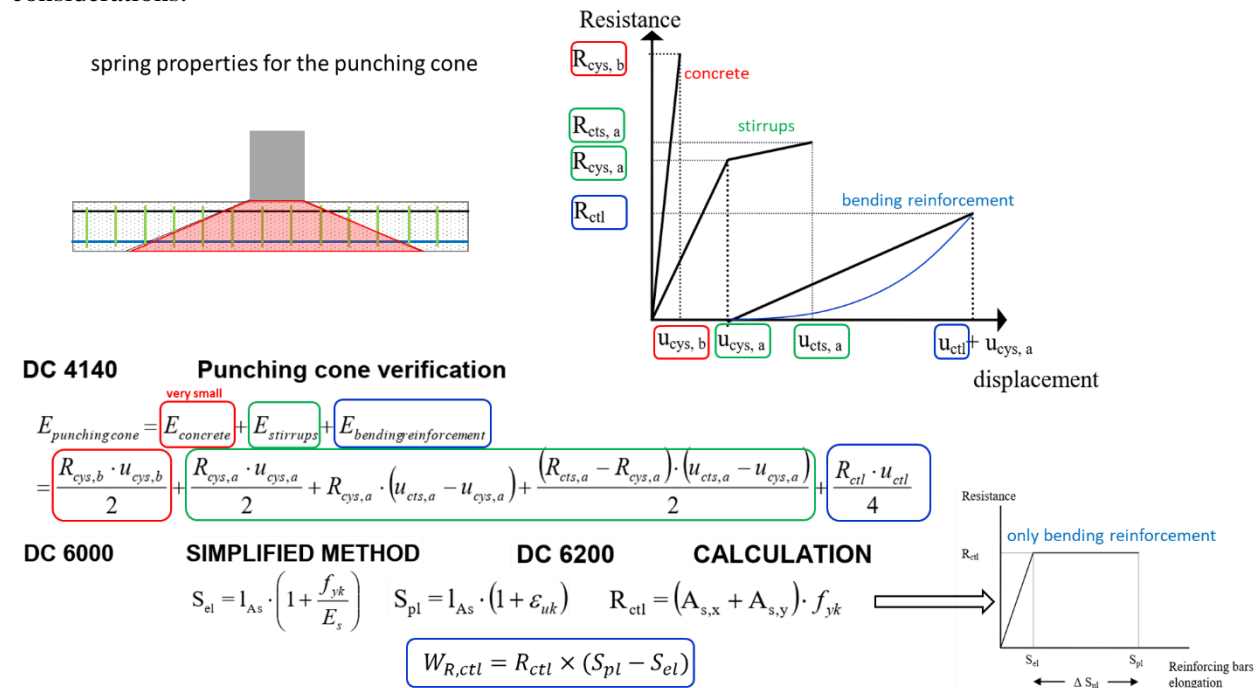


Figure 1. Energy balance check for the punching cone in RCC-CW code

The energy balance check in DC 6000 is supposed to be more conservative than in DC 4140 since it only considers the energy absorbed by the bending reinforcement through membrane action and ignores the contribution of the concrete and the shear reinforcement. However, the desired conservatism is not always achieved since the DC 6000 approach is considering a fixed punching cone angle of 26.6° . There is no clear advantage of the simplification introduced in the DC6000 and having two different formulae for the energy balance check in the DC Appendix is confusing the user. Simplifying assumptions can be handled by the energy balance check in Eq. DC 4140-1.

The PG3 suggested the removal of the chapter DC 6000 from the code. Furthermore, additional explanations to the current energy balance check formulation in DC 4000 for both the punching cone verification and the bending energy verification, as well as the limits of their application range should be added, to ensure correct application and to improve the user-friendliness. In general, the provisions of DC 2000 (lumped mass-spring model) should be enhanced in order to improve the user friendliness and to allow an easier application of the method.

Specific Provisions for Nonlinear Impact Analysis

Currently RCC-CW supplies general provisions for nonlinear structural analyses. However, specific provisions regarding nonlinear impact analyses with the finite element method are missing in the code. Detailed nonlinear structural analyses with the finite element method may be needed when a simplified approach is not appropriate for the complex boundary conditions loadings, and failure modes or in order to avoid the excessive conservatism. General provisions for nonlinear structural analysis are disclosed in RCC-CW code in DCONC 4230 “Structural Analysis/Nonlinear Analysis” and DJ 1000 “Informative Structural Capacity for Reinforced Concrete Elements/Material Properties”. Specific provisions for nonlinear impact analyses are provided below.

General considerations:

Missiles (or projectiles) that cause mechanical impacts are broadly divided into two categories: hard and soft missiles. The classification is generally based on the deformability and material strength of the missile in relation to the deformability and material strength of the object being struck. Therefore, it is possible to classify an impact type according to these two main missile categories.

Identifying the impact type and corresponding governing structural response phenomena (bending, punching, combined bending and punching responses) to be simulated is important for making the right modelling assumptions (e.g., analysis method, finite element types, sizes, model domain, constitutive relations, etc.). Depending on the identified structural response phenomena and on the damage level, a so called “decoupled” or “coupled” (i.e., integral simulation) approach may be used for the analysis of the missile-structure model.

Using a “decoupled” analysis, a predefined load-time function due to a soft missile impact (e.g. obtained by Riera’s approach) is applied on the target structure. This analysis method can be used when the bending mode is the dominant structural response phenomenon. Moreover, it can be applied where a combined bending and punching response of the structure is expected but the perforation of the target can clearly be excluded. In this case, finite element modelling using plane elements (such as shell element) can be considered.

When the punching response of the structure is expected (i.e. hard impact), or in case of a combined bending and punching response leading to a perforation, a “coupled” (i.e., integral simulation) modelling approach can be used. Using this approach, the structure is modelled along with the impacting missile. Accordingly, the missile penetration and tunnelling can be properly considered. In this case, either finite

element solid elements to represent the concrete target (care must be given to define concrete failure or erosion criteria), or methods well suited to simulate concrete fragmentation (Smoothed-Particle Hydrodynamics, SPH, lattice discrete particle method, discrete element method...) can be used.

Computational approaches:

Structural response analyses range from simple analyses (e.g. Appendix DC 2000 provisions of RCC-CW) to nonlinear detailed finite element or discrete element analyses.

Based on the expected structural response of the impacted target an appropriate finite element code and the type of model, as well as the type of elements and the material constitutive models can be chosen. Lagrangian finite element analysis, using beam, truss, shell and solid finite elements, is commonly used. Discrete element methods and the SPH method are also possible choices for certain problems.

Major Finite Element Analysis and Simulation Steps:

It is recommended to perform the detailed nonlinear analyses for the structures subjected to the impact loading using the following steps:

Step 1: Building the Team of Analysts

The first and maybe most important step is to choose knowledgeable and experienced members of the analysts' team. The strong technical background and experience of the analysts in the type of problem concerned is vital to setting up adequate numerical models and achieving reliable results. Only calculation codes and tools familiar to the team should be used.

Step 2: Preliminary Analysis

Before conducting any detailed nonlinear analyses, it is recommended to carry out a preliminary analysis of the given problem. Verified engineering tools based on simplified methods, empirical formulae, analogy (and transferability) to previous problems and with existing tests shall be used for this purpose (see Appendices DC2000, and DD of the RCC-CW code). The preliminary results shall be gathered, evaluated and discussed in order to make the right modelling assumptions, as for example:

- the rate of loading: impulsive, dynamic or quasi-static loading;
- the order of magnitude of the main parameters: expected duration of the impact, energy, momentum, expected strains and displacements;
- the expected structural behavior of the missile and of the target (local resistance to penetration/perforation or punching behavior, global or semi-global flexural behavior, combined flexural and punching behavior). The expected structural response has an influence on the choice of modeling strategy;
- design acceptance criteria: acceptable damage (e.g. deflections and rotations to of the target), performance of the target after the impact (e.g. requirement of leak-tightness).

Step 3: Choice of Tools, Modelling, and Validation of Input Data

Appropriate finite element codes and tools should be chosen in order to represent the physics of the structure. The type of model of the impacted structure and the missile, the type of elements and the material constitutive laws should be selected thoughtfully. Sensitivity studies on mesh sizes should be performed in order to develop a reliable finite element model. A finer discretization may be needed around areas where

stress concentration is expected. The mesh sizes for the first iteration could be chosen according to (IAEA 87 Safety Report 2018, Chapter 4.2.3.1.) recommendations.

The finite element model (incl. chosen constitutive laws) should be calibrated using representative experimental results, e.g. IRIS_2010 and IRIS_2012 for reinforced concrete. However, due to the numerous possible ways for matching the tests results, it must be ensured that the selected approach does not cause either a numerical or a physical law violation.

Step 4: Numerical Simulations

Sensitivity studies need to be carried out on main physical and numerical input parameters to investigate their contribution to the uncertainty in the analysis results, at a minimum: on the element size, the time step, key parameters of the material constitutive laws, the boundary conditions, and the failure (or erosion) criteria. The stability of the results in case of small changes of the parameters must be assured.

Due to the inherent uncertainties in nonlinear simulations the sensitivity studies can be used to define upper and lower-bound solutions.

Step 5: Handling of Results

Key analysis results (e.g. displacements, stresses, strains, damage patterns and missile residual velocities) should be verified for plausibility against results obtained using the alternative simplified methods mentioned in Step 2, e.g. Appendices DC2000, and DD (perforation and scabbing of concrete targets impacted by hard missiles) in RCC-CW code. Since analysis by simplified methods often focuses on a few parameters, a set of simplified models can be considered.

An appropriate safety margin is recommended in the design in order to adequately consider uncertainties and to avoid cliff-edge effects.

Step 6: Independent Peer Review

Taking into account the level of complexity and the range of uncertainties, an independent review may be appropriate for nonlinear impact analyses.

Load Characterisation

There is only a basic information on the accidental aircraft crashes in RCC-CW (DGENR 3335). This includes design basis event, DBE (general aviation and military aircraft), as well as design extension events, DEE. However, the terms “general aviation” and “military aircraft” are not defined in the code, and the term “commercial aircraft” is not even mentioned. In addition, loading functions associated to those types of aircraft are not given in RCC-CW code. Typically, the loading functions of each type of aircraft are project-specific and typically safeguard (confidential) information.

However, there is an interest to present in the RCC-CW code some general information related to impact loading. This would provide an insight into the state of the art in this field, and help the designers to choose methodologies adapted to the requirements of each project.

Loading corresponding to a soft impact

Typical examples of projectiles leading to a soft impact are some tornado missiles such as automobiles, or aircrafts. In that case, the momentum of the missile is converted into impulse transmitted to the target.

The usual mean to determine the loading on a target due to a soft impact is the Riera method. According to this method, the mass and crushing strength of the missile is distributed along the fuselage axis. The crushing strength of the missile's structure induces instantaneous and homogeneous deceleration in the remaining uncrushed part of the aircraft. The impact is assumed perfectly soft: the target is rigid, the projectile is deformable and there is no rebound (AN: usually a vertical impact -normal to the surface- is considered). Then, the application of Newton's second law leads to the loading, expressed as a force varying in time during the impact, applied on a surface depending on the geometry of the projectile. The area under the load-time-function is equal to the initial momentum of the missile.

Another way of assessing the impact forces is, as mentioned earlier, to use an explicit model of the projectile in a fast dynamic finite element analysis. In this case there are two possibilities: either the load-time function obtained from the analysis is applied to a model (simplified or finite element) of the target, or the explicit model of the projectile is part of a so-called integral simulation in which the dynamic missile-target interaction is analyzed. In this case, the contact forces between the two structures are output data, used only for verification purposes.

Whatever the approach, it is recommended to check that the momentum and the kinetic energy associated with an assumed loading function match the characteristics and the impact velocity of the projectiles chosen in the hazard scenario. In certain impacts, such as those of commercial aircraft, the missile can comprise a significant mass of fuel (liquid). Some experimental evidence and numerical simulations point out some rebound of the liquid on the target may happen, leading to an impulse greater than the initial momentum of the aircraft. It is recommended to take that effect into account in the load-time-function.

For the purpose of the structural analysis, the crash loading function is applied on a realistic surface on the structure, corresponding to the shape and dimensions of the different parts of the projectile that contribute to the loading.

Loading corresponding to a hard impact

Typical examples of projectiles leading to a total or partial hard impact are turbine missiles (created by turbine generator disk failure), dropped loads, tornado missiles such as thick-wall steel pipes, or aircraft engines and landing gear.

The contact forces due to a hard impact are frequently not easy to determine. They cannot be derived by the Riera method; results of tests can help. The duration of such impacts is often short: a few milliseconds, compared to tens or hundreds of milliseconds for the soft impacts. In addition, the impulse transmitted to the target is comprised between the initial momentum of the missile and twice that momentum, the latter case corresponding to an elastic shock, with perfect rebound.

In fact, the definition of the load depends on the type of analysis chosen by the engineer:

- empirical formulae, for the prediction of penetration, scabbing or perforation of concrete structures (AN: appendix DD of the RCC-CW). Those formulae were generally established for hard impacts. Concerning the missile, the input data needed are the mass, the impact velocity and the cross section;
- simplified methods for which a time-history of the impact forces is needed. In that case, based on assumptions concerning the impulse transmitted to the target and the duration of the impact, a mean force may be estimated. That rough guess should be based on conservative assumptions, and considered with care;

- energy based methods. This type of analysis, frequently used for dropped loads, does not require the time-history of the loading, but only the mass, the impact velocity and the cross section of the missile;
- finite element analyses involving an explicit model of the missile and of the target. In that case the contact forces are an output of the analysis.

Some objects that had been classically considered as hard missiles are partially deformable. This is the case of engines of commercial aircrafts, and, to a lesser extent, engines of military aircrafts, which have been studied in finite element analyses, giving way to more realistic load-time-functions. The latter have been tested, scaled and simulated during the Sandia tests in the 80's, leading to the proposal by Sugano et al. (1993) of reduction factors to be introduced in the existing empirical formulae (AN: these factors are already provided in NEI and IAEA guides previously mentioned).

Design Criteria for Structural Verification

Currently in RCC-CW code, information regarding the design criteria, and some engineering requirements, for the local verification of areas potentially exposed to short duration impacts like APC, dropped loads and similar appear in different sections DC 5000 and DCONC 10000. These seem to be dedicated to military aircraft impact.

A clear statement in RCC-CW regarding the APC and other impacts design criteria would improve consistency of the code, and significantly help designers. It is proposed to introduce two tables, a first proposal of which is presented in Tables 1 and 2 below. The criteria values presented in the tables are examples from a few projects or guidelines and may be adapted in the framework of each project. Among others, useful references may be RCC-G code (1988) for general aviation, KTA draft 2203 (1993), ETC-C code (2006), IAEA (2018, as well as NEI (2011) for the other impact hazards.

Table 1: Proposed assessment of structural performance and acceptance criteria; adapted from literature e.g., IAEA (2018) and NEI (2011)

Safety requirements	Behavior requirements	DBE acceptance criteria	DEE acceptance criteria	Possible assessment methods
no structural interaction (pounding) of adjacent buildings	limitation of structural displacements	maximum displacement smaller than 50 % distance between structures	maximum displacement smaller than 70 % distance between structures	Finite Element Method (FEM)
overall stability (bending and shear)	limitation of the strains in concrete and rebars limitation of rotations on supports	examples: rebars 1 % concrete – 0.35 % rotation slabs 4°	examples: rebars 2.5 or 5 % concrete – 0.5 % rotation slabs 6°	FEM or simplified models
local stability (punching)	no perforation	conservative assessment	less conservative assessment; with high confidence in the results	empirical formulae or simplified models

no damage to SSC behind structural member	no scabbing	conservative assessment	less conservative assessment, with high confidence in the results	empirical formulae
SSC anchorage to the structural member	limitation of concrete cracking	to be defined	to be defined	FEM
confinement of radioactive material or leak tightness (release control)	limitation linked to overall stability and: a) no tearing of the liner b) or no through-wall cracking, such as cone cracking	conservative assessment of: a) limitation of the liner deformation b) no through-wall cracking	Less conservative assessment (with high confidence) of: a) limitation of the liner deformation b) no through-wall cracking	a) FEM b) simplified model c) empirical formulae

Table 2: Proposed structural acceptance criteria; adapted from literature, e.g., from IAEA (2018) and NEI (2011)

Material failure limits			
Material	Strain Measure	DBE limit	DEE limit
Reinforcing Steel	Tensile strain	1%	5%
Concrete	Compressive strain	0.35%	0.5%
Post-tensioning steel (ungrouted)	Tensile strain	1%	3%
Post-tensioning steel (grouted)	Tensile strain	1%	2%
Carbon steel liner	Membrane principle strain	0.3% or 1%	2% or 5% (to be justified by testing)
Support rotation			
Structural element	Controlling mechanism	DBD limit	DED limit
Beams	Flexure / shear	Elastic behavior	2° to 3°
Slabs	Flexure / shear		4° to 6°
Columns and members in compression	Flexure / compression		2°
Shear walls and diaphragms	Flexure / in-plane shear		1.5° to 2°

CONCLUSION AND OUTLOOK

This paper discusses some code evolution proposals for the RCC-CW code regarding APC and other impact loads and corresponding design criteria made within the framework of the PG3 of the CEN/WS 64 Phase 3. The proposals were submitted by the PG3 to AFCEN according to CEN WS064 procedure. AFCEN has commented on these proposals, and they are being discussed by the experts' group in charge of the code modification process. The aim is to improve the code and incorporate part of the proposals for the 2025 edition. Depending on the complexity level and the technical depth of the proposed topics, however, some of the proposals may only be partially mirrored in the next edition of the code. Additionally, a few topics may further be discussed in the fourth phase of PG3 in order to improve the proposed recommendations.

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