NEBOJSA ORBOVIC'S GREAT ENTHUSIASM FOR NUCLEAR SAFETY

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ABSTRACT

Nebojsa Orbovic, fondly remembered by his colleagues and peers as "Neb," was well known for his extraordinary passion for civil and nuclear structures, broad knowledge, and a keen interest in new technical challenges. During his career, he made significant contributions to the safety of nuclear structures by proposing several innovative and versatile research projects he passionately undertook with success. He joined the Canadian Nuclear Safety Commission in February 2008 where he was a Technical Specialist in the Engineering Design Assessment Division of the Directorate of Assessment and Analysis.

Neb obtained his Dipl. Ing. (MSc) in Structural Engineering at the University of Belgrade, Serbia and began his career the same year at INGEROP, a French consulting company based in Courbevoie, in the Paris region. He worked there until 2004 as a civil/seismic expert reviewing seismic design and assessing a wide range of nuclear facilities. He worked as a designer on large infrastructure projects such as high-speed railway (TGV Brussels–Marseilles) bridges and the access viaducts at the Paris – Charles de Gaulle Airport. In 1996, he joined the Institut de Radioprotection et de Sûreté Nucléaire (IRSN), also in the Paris region. In 2004, he emigrated to Canada and joined Atomic Energy of Canada Limited (AECL), working on the Advanced CANDU Reactor (ACR) designs ACR700 and ACR1000.

Neb held several leadership positions within the Nuclear Energy Agency, International Atomic Energy Agency, American Concrete Institute, American Society of Mechanical Engineers, American Society of Civil Engineers, and International Association for Structural Mechanics in Reactor Technology. He was a member of the American Society of Civil Engineers and Earthquake Engineering Research Institute. He was a licensed engineer in the Canadian provinces of Ontario and Quebec and a voting member of the ACI 349 Committee for Nuclear Safety-Related Concrete Structures and ASME Section III Division 2 for Concrete Containments

INTRODUCTION

Nebojsa Orbovic had a plethora of professional colleagues around the globe. A recreation of his professional enthusiasm is possible only through the eyes of his peers. Here are three testimonies to set the stage for this paper. Jelena Manojlovic (2021) wrote that Neb "lived in three countries and on two continents, travelled the world and made a titanic journey from dreaming about forming a rock band to becoming a nuclear safety expert. He was a serious professional, becoming proficient in French and English languages to sharpen his professional skills. He was a man of many talents and contradictions, with numerous friends. He was a dreamer and realist, sensitive and vulnerable but courageous and with strong convictions." Prof. Gail Atkinson (2021) of University of Western Ontario remembered her "many stimulating, friendly and enjoyable interactions with Neb on seismic hazard assessment over 20 years." She admired Neb's enthusiasm, intellectual curiosity, and ability to grasp and balance various issues." Another professional colleague of his, Catherine Berge-Thierry (2021), recalled Neb's "intellectual curiosity, the desire to always understand and progress, with the desire to share more than anything. These values, driven by his overflowing enthusiasm, have allowed us to initiate and animate beautiful projects".

His contributions to the nuclear industry, particularly to the nuclear structures and seismic hazard assessment, began in 1994, and since then, he has been pivotal in driving several research projects. Some of these research projects continued even after he immigrated to Canada and joined

Atomic Energy of Canada Limited and then the Canadian Nuclear Safety Commission (CNSC). The objective of the paper is to provide a summary of his contributions to nuclear structural engineering.

STRUCTURAL IMPACT AND BLAST TESTING

He realized the importance of protecting nuclear facilities under external natural and human-induced hazards. This realization included the effect of combined seismic, impact, blast and high wind loads on structures. He was a pioneering member of the CNSC to start the structural impact and blast testing along with analyses. He participated in the IMPACT Test Campaign at the VTT Technical Research Centre of Finland; the American Society of Mechanical Engineers (ASME) blast tests at Oregon Ballistic Laboratories; and a series of NEA impact simulation benchmarks under the IRIS project (Improving Robustness Assessment of Structures Impacted by a Large Missile at Medium Velocity).

The IMPACT Test Campaign performed more than 200 tests starting from 2016, with Neb's (2017) participation in almost all of them, to assess flexural and punching behaviour of reinforced and pre-stressed concrete slabs and the impact-induced vibrations. The campaign aimed to establish acceptance criteria for structural missile impact design and calibrate numerical models. The test design assessed the influence of different structural features such as pre-stressing and transverse reinforcement and the influence of longitudinal reinforcement on the structural behaviour of concrete slabs under impact.

The Joint Task Group of ASME and American Concrete Institute (ACI) established and conducted the ASME blast tests. Neb was an active member of both committees. The tests were performed on pre-stressed concrete slabs to establish structural acceptance criteria for nuclear containment structures under impulsive loading. These tests, conducted with pre-stressed concrete slabs of 4.88 m x 4.88 m x 0.27 m, represented typical nuclear containment with different pre-stressing levels and different reinforcement ratios. Figures 1 and 2 show a concrete slab under construction and Neb's enthusiastic inspection of the post-test wall. After ASME and IMPACT tests, the results are employed for the ASME and ACI code provisions update and, eventually, to update CNSC regulatory documents.

Figure 1. Concrete slab used in ASME blast test

The NEA simulation benchmarks IRIS_2010, IRIS_2012, and IRIS Phase III (2017) were put in place to provide technical guidance for the numerical simulations of structures impacted by deformable (soft) and undeformable (hard) missile impacts. Over 25 teams from 10 countries participated in these benchmarks. The IRIS organizing committee, supported by the scientific committee, published NEA reports with technical conclusions from these benchmarks and recommendations for verification and validation of numerical simulations.

Figure 2. The post-test view of ASME blast test concrete slab

THE ALKALI-SILICA REACTION

Another phenomenon that attracted Neb (2018, 2019) was the alkali-silica reaction (ASR), an alkali-aggregate reaction observed in some concrete structures in eastern North America, Europe, and Japan. He realized the significance of the degradation potential to civil structures. He and his international colleagues joined hands with the OECD Nuclear Energy Agency to put a three-phase international research program, Assessment of Structures Subject to Concrete Pathologies (ASCET). Phase I of the project was related to the general recommendations for the aging of concrete structures with concrete degradations, while Phases II and III were related to the numerical simulations of three ASR and two regular concrete squat shear walls with the same geometry and reinforcement. All shear walls, were manufactured and cured under accelerated aging at the University of Toronto, under a CNSC research program. The phenomena were numerically simulated and benchmarked in ASCET Phases II and III. The pre-and post-test view of the shear walls is shown in Figure 3.

Although Neb was not a computer modeller, he encouraged other members of the CNSC to participate in numerical simulations. Nine teams from Canada, France, Japan, Sweden, and the United States participated in the ASCET benchmark. Using different approaches, most participants used commercially available software and modelled the ASR concrete degradation. The ASCET Phase II benchmark consisted of blind simulations of shear walls tests with ASR and regular concrete after 995 and 975 days of accelerated aging. To calibrate the numerical models, the organizing committee provided the participants with the tests results of the ASR and the regular concrete after 260 and 240 days of accelerated aging. In Phase III, the organizing committee provided the participants with all available information on these four walls and, in addition, the test results of one ASR concrete wall tested after 610 days of accelerated aging. All the walls were loaded using the same protocol. The amplitude of the cyclic loading increased gradually up to the failure of the wall. This benchmark considered the maximum shear (ultimate) capacity, failure modes, crack patterns, structural ductility, and energy dissipation.

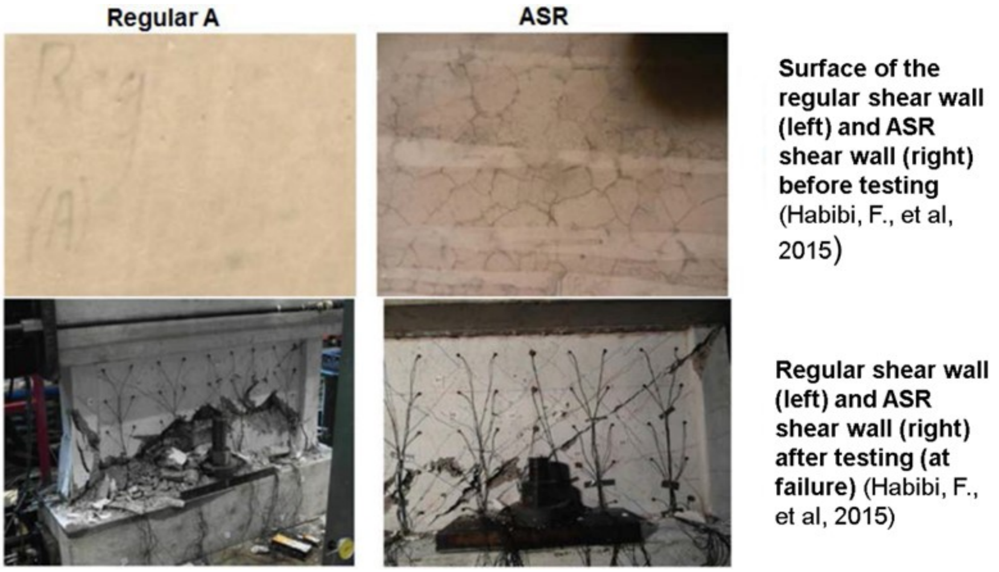

Figure 2. The post-test view of ASME blast test concrete slab

The findings of the testing program were: 1) ultimate wall capacity was not affected by ASR, and 2) structural ductility and energy absorption (hysteretic damping) decreased significantly. All participants successfully simulated the ultimate wall capacity. However, the simulations of failure modes, crack patterns, structural ductility and energy dissipation were unsuccessful.

DESIGN MARGIN ASSESSMENT FOR BEYOND DESIGN BASIS EARTHQUAKES

Anyone who had come across Neb (2021) professionally would vouch for his passion for design margin assessment of existing nuclear power plants (NPPs), mainly for beyond-design-basis earthquakes (BDBE). He would be very animated when someone broached this topic. His quest started in the 1990s with the EPRI methodology for seismic margin assessments and seismic probabilistic risk assessments. The primary purpose was to assess the structural limits for existing NPPs and propose beyond-design-basis acceptance criteria that would allow for the primary safety functions: safely shutting down the reactor, cooling the reactor, and maintaining the leak tightness of the containment system. Later the design margin assessments included the assessment of the containment's capacity to withstand pressure loads beyond the design pressure. The loading assessments of nuclear power plants after September 11, 2001, included commercial aircraft crashes and large-area fires, which were absent during the design phase of these plants.

Furthermore, EPRI provided a methodology for BDBEs (or review level earthquakes) to assess the structural capacity of existing NPPs by using acceptance criteria that are less stringent than those currently in the ASME Code (high confidence of low probability of failure (HCLPF) or conservative deterministic failure margin (CDFM)), but which are still sufficient for maintaining the main safety functions.

Neb assisted in several International Atomic Energy Agency documents. The development of the International Atomic Energy Agency's international safety standards and the regulatory documents in the U.S. and Canada led to new requirements for the design of new NPPs, during the design phase assessments, for limits of safe operation of the reactor, as well as any potential cliff-edge effects for loading cases exceeding the design limits. These standards also required the designer to modify the design if necessary. The Fukushima accident justified and reinforced this approach. In line with this approach, what was called beyond design basis for the assessment of current existing plants is now called design extension conditions and design extension external events for the design of new builds. The idea is the same: to provide acceptance criteria that, despite relatively heavy plastic deformation and structural damage, will allow for the availability of the same main safety functions of safely shutting down the reactor, cooling the reactor and maintaining the leak tightness of the containment system.

Modern design codes and standards recognize the existence of loading conditions higher than design-basis loading conditions and provide design acceptance criteria for these conditions. The containment design specifications for new builds now require consideration of design extension conditions and design extension external events. The current ASME (American Society of Mechanical Engineers) Section III Division 2 Code for the design of nuclear concrete containment structures is based on allowable stresses and essentially elastic behaviour under the application of primary forces. Essentially elastic behaviour is required for all external loading cases and induced primary stresses, except impactive and impulsive loading for which elastoplastic behaviour is allowed.

Neb's contributions discussed above help open numerous justifications for design criteria. In particular, the need to provide the designer with criteria for the containment building's structural integrity and leak tightness under loading cases higher than design-basis loading cases. Depending on the loading cases (seismic, overpressure, impactive/impulsive), the acceptable structural behaviour and the design margins, in terms of the conservatism of code provisions in the elastic domain and the potential excursion to the plastic domain, will be different. The structural behaviour will not remain elastic, but by the time this will occur the safety functions of containment will still be fulfilled. Impactive/impulsive loading will affect only a limited portion of the containment structure. The overpressure load will affect the whole containment building, while a seismic load will lie in between these two cases; that is, the loading will affect the whole structure, but the maximum forces and ductility demand may be localized. Therefore, in terms of deflections and strains, the acceptance criteria should be the most stringent for overpressure loading and the least stringent for impactive/impulsive loading. These valuable discussions on acceptance criteria will continue as a testament to Neb's contributions.

CONCLUSIONS

Nebojsa Orbovic was an astute professional, friend, colleague, mentor, and researcher. He stood apart from whatever role we knew him as someone special we all can remember him. Neb was committed to research and focused on improving nuclear safety and structural design. He was passionate and enthusiastic about structural engineering and civil engineering. He was a leader and change agent who had grand dreams of assessing the integrated effect of seismic, impact, blast and high wind loads on structures.

Neb's memory with us is to continue the work he envisioned and mentored many international colleagues in our respective countries and advance the unfinished activities when his life was cut too short so suddenly. There are still some loose ends with the Alkali-Silica Reaction research projects, perhaps will continue until the knowledge level improves and uncertainties are reduced to acceptable levels.

It was a privilege for those who had the opportunity to debate his strong views about modern design codes and standards that recognize the existence of loads higher than design-basis loads. He would argue that the design considers only elastic behaviour based on allowable stresses, except for impactive and impulsive loading for which elastoplastic behaviour is allowed. Through his unwavering commitment to research and engineering practice, he made a significant and ever-lasting contribution to the community of structural mechanics and nuclear containment structures.

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