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DESIGNING RESILIENCE - CAPACITY DESIGN OF HINKLEY POINT C HEAT SINK

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Abstract: *After nearly 25 years, a new British nuclear power station is being constructed at Hinkley Point C (HPC), UK. A robust level of resilience is expected of the nuclear power plant, which is reflected in the strict UK regulatory requirements. As this takes place post-Fukushima and several other significant seismic events around the world, the expectations for resilience in design are heightened. Therefore, a high level of resilience is required for the water-cooling supply system, which is the subject of this paper. As part of the cooling system, the heat sink consists of several marine structures, including the intake and outfall offshore heads. These offshore structures provide the required level of cooling water at any stage of the power plant operation, including extreme events such as a 1 in 10,000-year earthquake. Therefore, to ensure an adequate level of resilience, all plausible eventualities must be considered in the design. This paper discusses the civil design performance requirements for a class 1 nuclear safety related structure. It explores the use of force/strength-based design procedures working within the elastic stress range for design basis events. Combined with innovative performance-based ductile design, working within the plastic stress range to provide resilience against events beyond the design basis. The result is six extremely robust reinforced concrete structures which satisfy all UK regulatory requirements. This paper presents the capacity design approach, undertaken by Jacobs Engineering (designer), to design critical structural elements within the head structures. It discusses the concepts of forced failure mechanisms to ensure critical events cannot occur. Detail is given on the industry leading construction techniques employed by Balfour Beatty (contractor) and the advanced 3D reinforcement detailing created by specialists ADDA while being supported throughout by EDF's Nuclear New Build (client).*

Introduction

Project Background

A new nuclear power station is being constructed at Hinkley Point, Somerset (UK) by EDF. The new station will generate 3200 MWe of energy utilising two European Pressurised Reactors (EPRs). One of the critical parts of the station is the heat sink, which provides the cooling water to the station.

This primary cooling water supply for the station is fed from four submerged intake heads located on the seabed approximately 3.4 km offshore, in the Bristol channel. These heads are connected to the forebays and the pump house via two 6.0 m diameter intake tunnels which carry the water. Once the water has completed its cycle, it is discharged via onshore vertical shafts into a 7.0 m diameter outfall tunnel and returned to the Bristol channel via the outfall heads which sit approximately 1.8 km offshore. This type of offshore cooling water system is considered quite unique, with a number of challenges specific to the location within the Severn Estuary, known for having one of the largest tidal ranges in the world. A graphical representation of the offshore part of the heat sink system can be found in Figure 1, replicated after C, Kennedy (2020).

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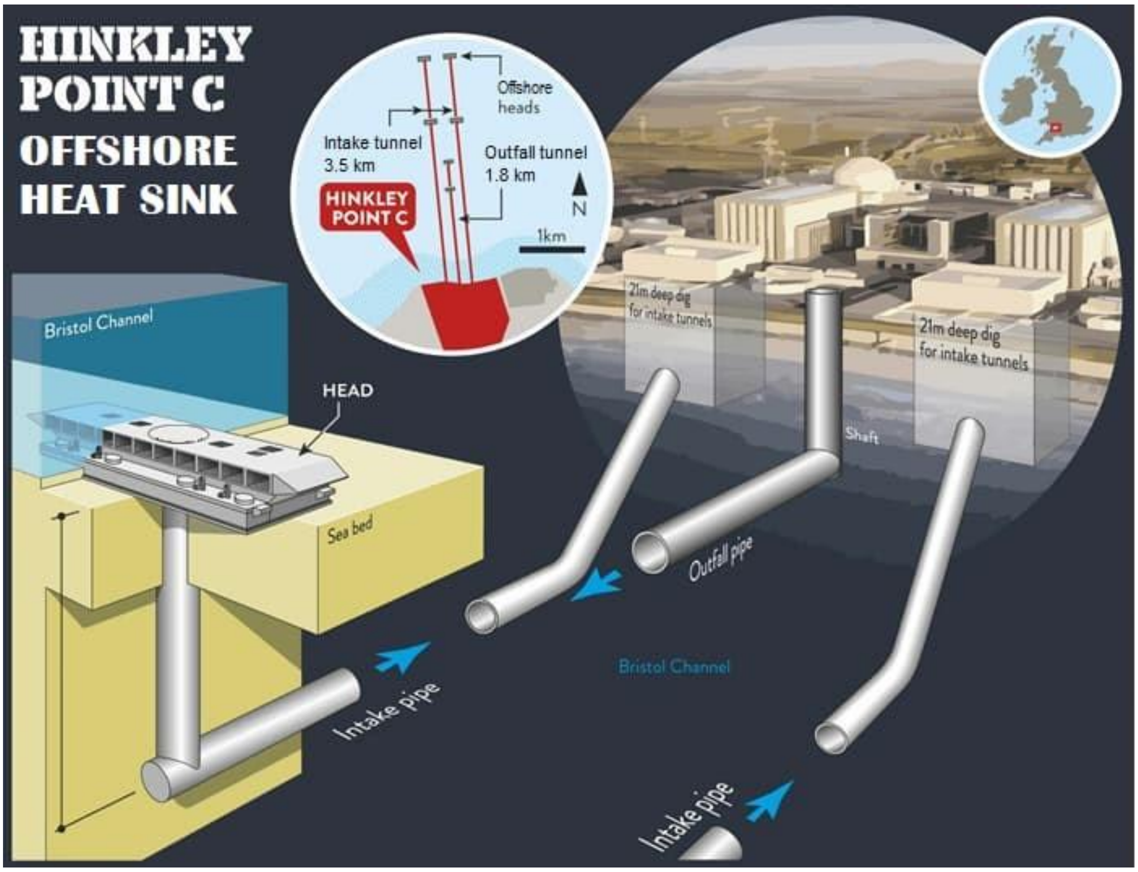

Figure 1. Arrangement of offshore heat sink structure - C, Kennedy (2020)

Offshore Structures

The main functional requirement of the offshore heads is to ensure a critical volume of cooling water is available to the facility at all times, including normal operations, shutdown scenarios and accidental conditions. These critical structures are designed to conform with the Safety Assessment Principles used in the Office for Nuclear Regulation (ONR) regulatory process within the UK. The project employed a class leading soil-structure interaction (SSI) analysis and dynamic response spectrum analysis to derive the structural demands within the elements, followed by an innovative approach to detailing, aiding performance and constructability.

Following the feasibility study and concept design, developed by the client, the work was procured as a design and build project, where the contractor and designer works closely together to deliver the successful solution.

The product of these efforts is four reinforced concrete intake heads and two outfall heads, complying with industry standards, including environmental requirements and nuclear safety aspects. A typical view of the intake head structure, which is the subject of this paper, is presented in Figure 2, where its key structural components are indicated.

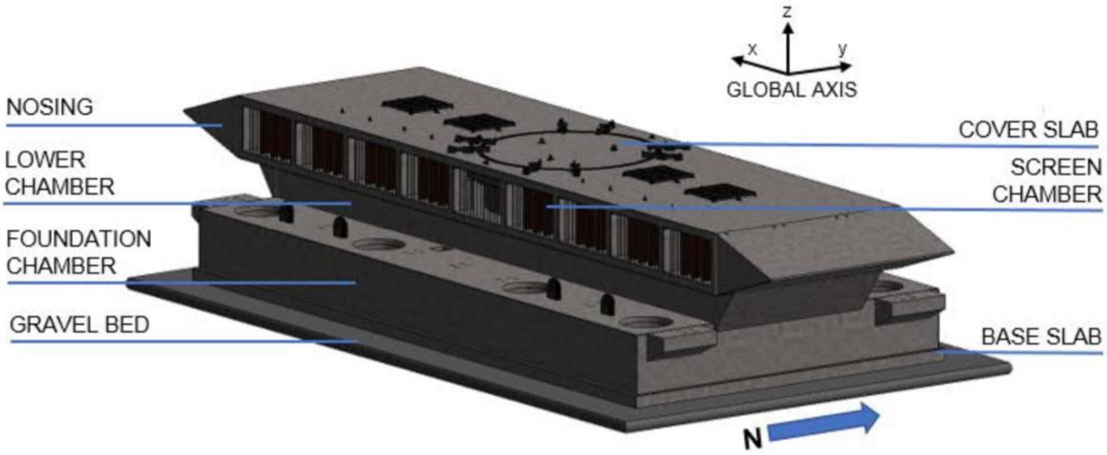

Figure 2. 3D view of intake head structure, indicating specific design structural members

A specific cross-section of an intake head structure is presented in Figure 3, where the screen chamber, lower chamber and foundation chamber are clearly identified, as well as expected load paths.

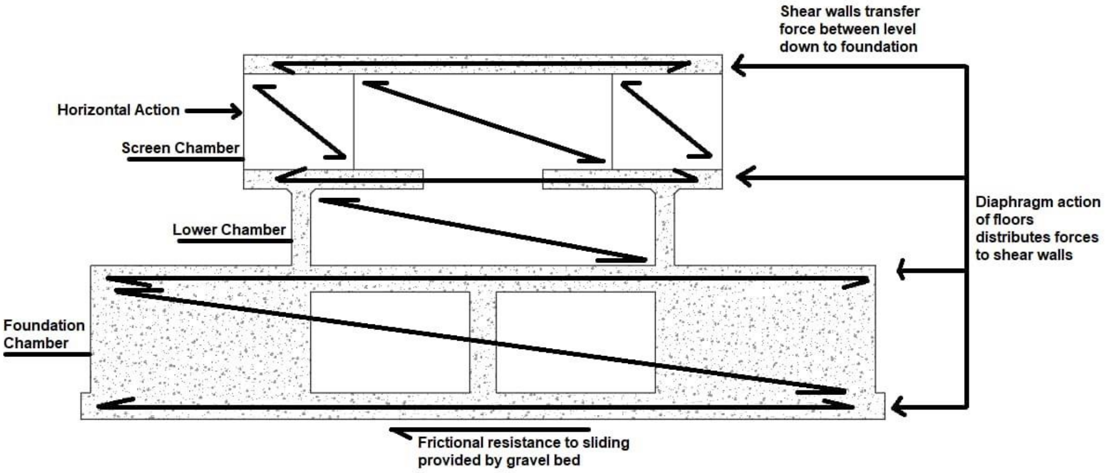

Figure 3. Cross-Section of intake head with indicative horizontal load paths

Resilience

Following on from the UK government guidance (Cabinet Office, Oct 2011), a concise definition of resilience can be summarised as the ability of assets, networks, and systems to anticipate, absorb, adapt to and / or rapidly recover from a disruptive event. Resilience can be secured through a combination of approaches, activities and or components, which are presented in Figure 4.

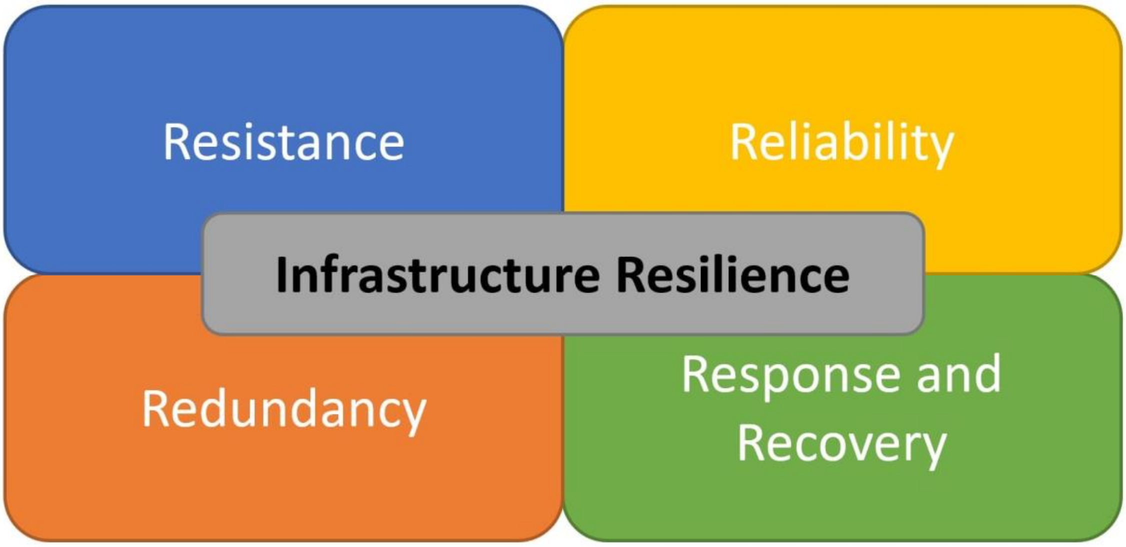

Figure 4. Components of resilience according to (Cabinet Office, Oct 2011)

A critically important part of this approach is the structural resilience, which is covered in detail within this paper. Details are provided through the design processes in subsequent sections, showing that the offshore structures have the necessary resistance, reliability, and redundancy. This includes the broader heat sink offshore system, since a single intake or outfall head can provide adequate levels of water flow through the system in an emergency condition. The response and recovery are provided by the client organisation, through the site management and procedures.

Requirements and Design Intent

The broader context of the requirements for a nuclear safety related structure in the UK is captured by ONR, 2021, Licensing Nuclear Installations. The ONR is the licensing authority for nuclear installations in Great Britain. The ONR brings together the regulatory functions for nuclear safety, nuclear security, nuclear safeguards, radioactive materials transport and conventional health and safety at nuclear sites.

Amongst other official regulations, the reduction of risk and the use of as low as is reasonably practicable (ALARP) principle is considered fundamental. Following ONR, 2021, Licensing Nuclear Installations, ALARP can be explained as a requirement to take all measures to reduce risk were doing so is reasonable, rarely using an explicit comparison of costs and benefits, but rather applying established relevant good practice and standards, which are based on ALARP in the first place.

Seismic Design

Following on from the lessons learnt from the Fukushima nuclear accident, the seismic demand for UK nuclear related structures is enhanced by the additional requirement to consider effects and structural performance beyond the general design basis. For seismic design purposes a set of load cases is considered; this includes the Design Basis Event (DBE) with zero period acceleration (ZPA) of 0.25 g, corresponding to a 1 in 10,000-year seismic event. Additionally, the consideration of Beyond Design Basis (BDB) effects and structural performance as well as the impact from Uniform Hazard Spectra (UHS) established through Probabilistic Seismic Hazard Assessment (PSHA) is considered. The design is also required to comply with a seismic Inspection Event (IE), which is generally less onerous, corresponding to a 1 in 1000 years event but considered multiple times. As the structures during their design life will rest on the seabed, the seismic actions are considered in combination with other permanent and accidental cases related to the motion of the sea, such as swell, current and tide.

All these design cases are considered during detailed design and through the analysis and design processes, providing a robust solution for the reinforced concrete structures.

Safety functional/safety operational requirements

The ONR has established a suite of Safety Assessment Principles (SAPs), which guide regulatory decision making in the nuclear site license safety submissions. For a facility to attain a UK nuclear site license to operate, its license submission with be assessed by specialist ONR inspector using the ONR's SAP guidance with support of the Technical Assessment Guides (TAG).

Following on from the ONR process, client established safety functional requirements (SFRs) and safety operational requirements (SORs) are the key items to consider during the design process. These range from the requirements of withstanding the DBE seismic action to the durability of concrete in the marine environment. These cover structural design as well as environmental, buildability and maintenance aspects.

These SFRs and SORs in combination with the scope of works provide the basis of design. To ensure that the "golden thread", is maintained within the design process, a structural design method statement (SDMS) is produced, outlining all the relevant actions, their combinations, the analysis and design stages, and the materials used in the design and construction process, allowing the detailed design to proceed.

Design Substantiation

From the design perspective the final deliverables are production of drawings, specifications, designer's risk registers and for the nuclear structures the production of the Design Substantiation Report (DSR). A DSR is produced to confirm the adequacy of the design within the requirements context and demonstrating how the requirements in the basis of design have been achieved. All the design aspects are presented and discussed, with specific SFRs and SORs listed with substantiation statements made by the designer. This provides the "golden thread" between the initial client scope and the construction drawings, through structural design aspects within the context of the SFRs and SORs.

Seismic Civil Design Performance Requirements

Performance Requirements

There are primarily two methods of design of structural resilience against seismic DBE. The traditional approach i.e., strength-based design and the progressive approach i.e., performancebased design.

It should be noted, that provided a structure can absorb all of the seismic energy for the earthquake action, without collapsing, it has served its primary purpose. Depending on the performance of the structure, the level of damage and displacement may be significant, however, if the manner of failure is predetermined then significant gains in structural efficiency can be achieved.

A key concept in performance-based design is the ability for the structure to displace and deform as it absorbs the seismic energy in a predictable and detectable manner. The level of deformation is tied to the required level of performance, but ultimately leads to the expected non-linear behaviour without collapse of the structure.

The critical requirement for a UK class 1 nuclear safety related structure is to demonstrate that there is virtually no permanent damage to the structure during the 1 in 10,000-year return period earthquake and most importantly that there is no release in radioactivity into the atmosphere. Therefore, ensuring near elastic behaviour throughout the seismic DBE is critical to satisfying the safety functional requirements specified for the offshore heads and is the design approach presented in this paper.

The Traditional Approach – Strength/Force Based design

Traditionally in civil nuclear design, to demonstrate resilience against seismic DBE a strengthbased approach has been utilized. Strength-based, often referred to as "Force-based", ensures the structure will respond linearly to the seismic action and that it fully resists the forces generated within it. A Force-based design approach requires the structural elements have sufficient margin within its capacity to always act within the elastic range at DBE. As the sections respond elastically, the structure suffers limited damage and should be fully functional after a seismic DBE event. The downside of this, is the structural section sizes required to provide this level of capacity are relatively large compared to those determined using a force dissipation approach.

From an environmental standpoint this poses a significant issue. Taking in all stages of production, concrete is estimated to be responsible for 4-8% of the worlds CO2 emissions as presented in Lehne J and Preston F (2018) paper. In a day and age where the global climate emergency is more prevalent than ever, civil engineers have a duty to minimise the embodied carbon output of our industry as much as possible. One area where we can make significant gains, is the reduction of concrete use to as low as safely possible. This is where performancebased ductile design can really make a difference.

The Progressive Approach - Performance-based ductile design

By applying a ductile design approach, we allow the structure to respond to the applied seismic action in a non-linear ductile manner. This can be achieved through special detailing provisions, that allow the structure to redistribute and dissipate the seismic energy between its structural elements when undergoing non-linear deformation. This strategy is adopted by selecting distinct elements of the primary lateral force resisting system and suitably designed and detailed for energy dissipation under severe imposed deformations, with visual representation illustrated in Figure 5. By enabling the structure to deform in a safe, non-linear manner, this means it can absorb significantly more seismic energy than a corresponding elastic structure. Additionally, the ability to absorb the seismic energy is a consequence of much higher structural damping, than the equivalent elastic system. However, this can lead to excessive displacements of the structure, which are potentially non-recoverable.

Therefore, as aforementioned, for nuclear safety related structures it is a requirement, of the structure, to behave elastically under the seismic DBE motion, minimising any damage to the system. Consequently, ductile design for nuclear safety related structures, is reserved for beyond design basis scenarios. This poses an extremely rigid design requirement on any new civil nuclear build structures in the UK, which are predominantly constructed from reinforced concrete.

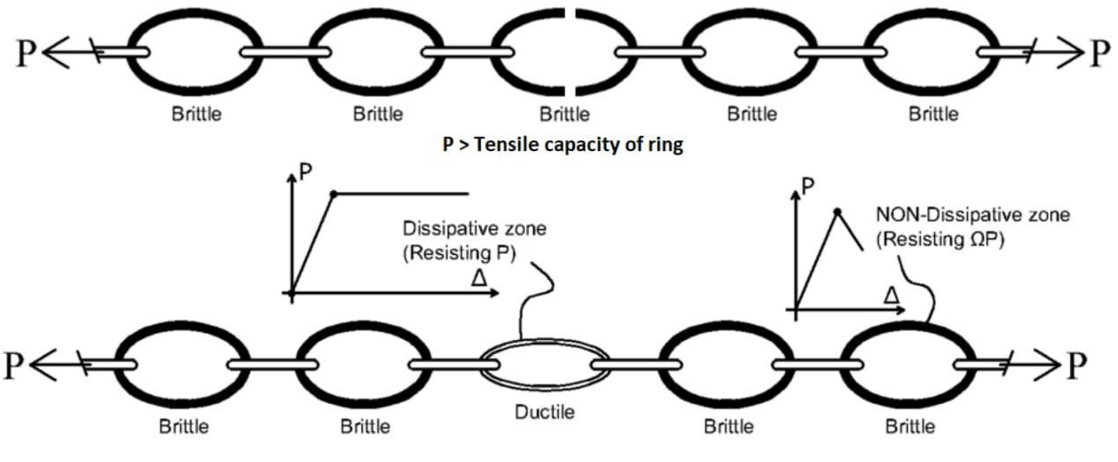

Figure 5. Principles of capacity design with ductile chain

Beyond Design Basis

To give context for the requirements of a Beyond Design Basis assessment, the Office for Nuclear Regulation, 2014 states that “a small change in design basis fault or event assumptions should not lead to a disproportionate increase in radiological consequences”. This is the fundamental principle of the ONR’s requirement to confirm the absence of “cliff-edge” effects for any beyond design basis events. An important part of the BDB assessment and a UK obligation, is to ensure all failure modes should be gradual and detectable i.e. cracking or excessive deformations of the structure should occur prior to collapse. This allows the structure to demonstrate clear signs of failure prior to collapse, thus being predictable and detectable, providing an opportunity to take corrective action.

For the intake heads, the BDB assessment initially focused on determining the potential failure modes that could occur and whether these were ductile or brittle. As previously mentioned, the heads are designed to behave elastically throughout the DBE event and therefore have a level of inherent ductility. Nevertheless, it is pertinent to identify the potentially brittle failure modes (typically shear) and provide an adequate strength margin to failure. This forms the basis of the BDB design approach utilised for the design of the heads. As a result, once the failure mechanisms are understood, brittle failure modes can be suppressed through considerate design choices.

Several key locations were identified as particularly critical to the safety function of the head structures and at these locations additional ductility detailing was applied. An example is discussed in the following section.

Capacity Design of the Intake Head Lower Chamber / Screen

The lower chamber walls of the intake head were identified as particular critical to the nuclear safety functional requirements of the head structure. Figure 3 illustrates the arrangement of the lower chamber walls which, if it were to collapse, the superstructure could block the intake shaft. This poses a significant risk to restricting the flow of safety critical cooling water into the facility. Through the analysis and design process, the DBE seismic load case was identified as governing for this location and therefore the BDB performance was of critical interest.

Generally, the orthogonal arrangement of the structural walls in the intake head ensure that they behave as braced structures. However, the longitudinal walls of the lower chamber are only braced by the end walls of the lower chamber, over a relatively short length in-board of the end walls. Further inboard, along the length of the longitudinal walls, resistance (normal to the plane of the lower chamber longitudinal walls) is provided by the portal sway resistance of longitudinal walls coupled with the floor of the superstructure and the roof of the foundation chamber.

Portal sway action under seismic action typically results in large lateral displacements (compared to the in-plane behaviour of structural walls) which under extreme seismic action, i.e. BDB seismic action, can lead to non-ductile out of plane shear type failures.

As a consequence of the foregoing, capacity design principles are applied to the out of plane design of the lower chamber longitudinal walls to ensure they yield in a ductile manner when subject to portal sway actions associated with BDB seismic action.

The capacity design approach results in the longitudinal wall out of plane (portal sway) behaviour being governed by flexural plastic hinges forming at the tops and bottoms of the longitudinal walls which are detailed to ensure that the ductile flexural plastic hinges form prior to any out-of-plane brittle type shear failures, away from the end walls. This provides a system with both ends braced by the orthogonal walls and ductile behaviour of the middle portion of the longitudinal wall.

This is achieved by equating the ultimate moment capacity of the section, following the Eurocode 2 rectangular stress block distribution to an equivalent shear force throughout the wall. To ensure compliance with EDF’s Technical Code for Civil Works (ETC-C) the process for determining Out of Plane Shear (OOPS) demand for equivalent shear forces is undertaken. Based on the actual shear demands, an equivalent bending capacity is recalculated and compared to the bending demand. Subsequently an iterative process is considered to ensure seismic forces are enveloped. As a result, the main reinforcement within lower chamber wall has utilisation in the range of 0.9 and the corresponding shear links utilisation is less than that, confirming that the vertical steel will fail prior to the OOPS steel. Since the vertical steel failure mechanism is in bending, it provides a gradual and detectable mode of failure. This in-turn ensures that this critical element, lower chamber section, provides the load path for the range of environmental actions, demonstrating additional resilience within the structure, even during the BDB event.

Additionally, any calculations related to brittle concrete behaviour are undertaken, checks include items such as concrete crushing, concrete compression strut angle limit and maximum concrete strain at the extreme fibre. Since the failure mechanism of this system is considered now a ductile one, utilisation ratios of up to unity are acceptable for bending behaviour.

Details of the foregoing approach are shown diagrammatically in Figure 6. A similar approach is undertaken at other locations of the structure, but not described in detail within this paper.

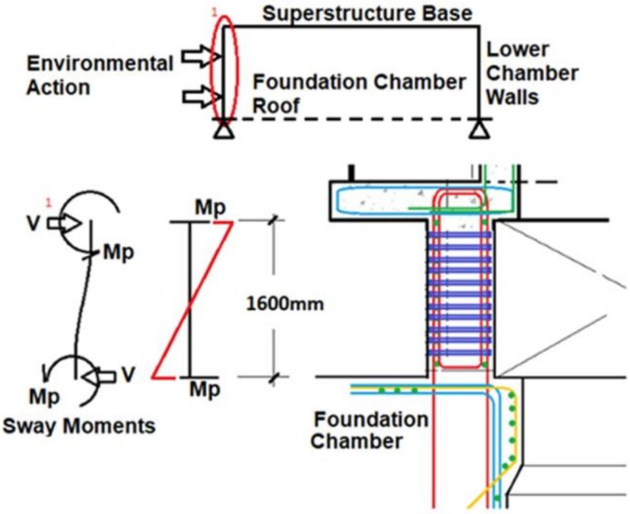

Figure 6. Sway moment mechanism in lower chamber walls

It can be concluded that by designing the intake head structure to respond elastically to design basis environmental actions and plastically at critical locations at beyond design basis, the result is a very resilient structure, which can provide the cooling water for the nuclear power plant at events beyond the design basis. It needs to be stated that the design resulted in challenging reinforcement detailing, especially at the interfaces within the superstructure. Due to the complexity of the interfacing reinforcement and to minimise construction issues on site a specialist subcontractor is employed to build the reinforcement in 3D. A fully clash detected, sequenced, 3D model is created, to demonstrate buildability and help understand a sequence on how these structures care built, in reality.

Innovation in seismic reinforcement detailing

Due to the high seismic demands, which consider all water effects, in combination with water flow optimised head geometry, the resulting reinforcement is very dense throughout most of the structure. Therefore, a specialist 3D detailer (ADDA) was subcontracted to build a detailed reinforcement model (Figure 7). The 3D model builds the structure from the ground up, in a process that accords with actual construction process, individually sequencing bars in such a way as to demonstrate that each subsequent layer could be placed without clashing with another adjacent bar in a virtual environment.

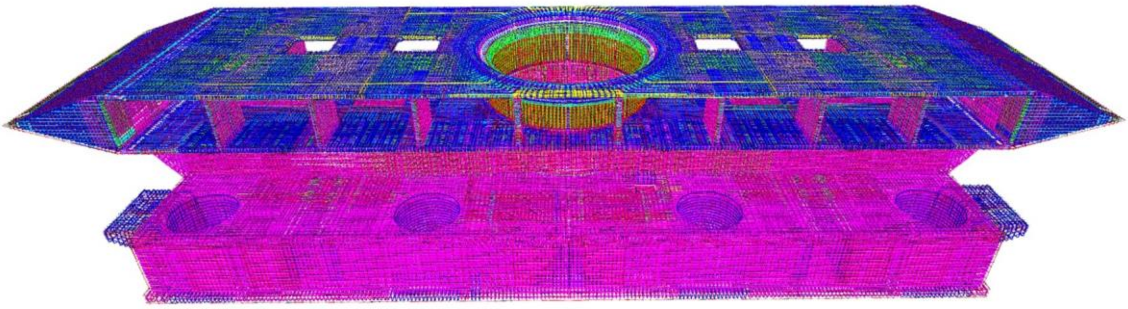

Figure 7. 3D Reinforcement model of the intake head

Each bar within the model is assigned metadata which identifies among other things its size, weight, layer and section number. Tagging each bar allows quick identification within the model and the ability to review elements in isolation. The bar tags are linked with the bar marks on the bar bending schedules, used by the manufacturers. These are also used for quality inspection when arriving on site. As the model is developed the bar interfaces become more and more complicated, with reinforcement extremely dense at some of the interfaces. At set intervals a clash detection workshop is scheduled to discuss and review any bar clashes, with collaborative resolution, by general adjustment to ensure placement is possible on site. The team was able to confirm digitally that the installation of rebar would be achievable with a high confidence factor, using computer aided processes. Additionally, accurate sequencing and placement led ultimately to reduced costs and provided confidence in the construction schedule.

Conclusion

This paper presents the innovative civil design approach applied for the construction of six submerged reinforced concrete heads. These structures form an integral part of the heat sink system providing the cooling water for the new nuclear power station constructed at Hinkley Point in the UK.

This paper discusses the current UK regulatory requirements for the design of a class 1 nuclear safety related structure and provides context to the level of resilience expected of such a system. Focus is given to the performance requirements expected of the structures to resist extreme load events and discusses the pros and cons of the traditional vs progressive civil design approaches.

A requirement of the Office of Nuclear Regulation is to demonstrate structural resilience for events beyond design basis. The paper presents an innovative approach to civil design for handling this magnitude of loading. A case study of a critical location of the HPC intake heads is described where expected failure mechanics were studied and determined. At this location a progressive capacity design approach is applied to suppress any brittle failure modes and ensure a predictable and detectable ductile failure occurs first.

By following the traditional design approach, the structural sections in this location would have been increased in dimension to accommodate the increased loads. However, by applying performance-based design principles the structural section sizes were able to remain optimised, therefore, reducing the amount of concrete required.

This goes to show that with a deeper understanding of our structures and their failure mechanics we are able to reduce our carbon footprint through clever and conscious design choices.

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