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Parameter study for a dimple location in a space grid under the critical impact load †

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Abstract

The spacer grid assembly, an interconnected array of slotted grid straps embossed with dimples and springs, is one of the main structural components of a pressurized light-water reactor (PWR). It takes the role of supporting the nuclear fuel rods which experience a severe expansion and contraction caused by harsh operational conditions such as an earthquake. The external load by an earthquake can be mainly represented as a lateral load, and the resistance to it is evaluated in terms of dynamic crush strengths. It has been reported that a dimple location in a space grid has an effect on this strength. In this paper, based on this fact, the effect of a dimple location in a 3×3 support grid on impact strength has been investigated as a preliminary parameter study for a full sized support grid. The optimal location of the dimple, about 3.5 mm from the tip of the strap, has been found and some design guidelines for a support grid such as reducing the spring length and the dimple gap have been provided.

Keywords: Spacer grid; Nuclear fuel assembly; Impact strength; Dimple; Optimization

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1. Introduction

Nuclear energy has been paid attention as an indispensible energy source and many countries nowadays try to increase nuclear energy production due to the high gas price. The safety issue of a nuclear plant always deserves special emphasis and many researchers have studied how we can a design robust and reliable nuclear plant. This paper especially considers designing a fuel assembly in a pressurized light-water reactor (PWR) under a harsh impact load such as an earthquake. The fuel assembly consists of spacer grids, fuel rods, a top nozzle, one bottom nozzle, guide tubes, and an instrumentation tube as shown in Fig. 1. Among them, the spacer grid assembly is an interconnected array of slotted grid straps, welded at the intersections to form an egg crate structure as illustrated in Fig. 2 and Fig. 3. The spacer grid assembly supports and protects the fuel rods from external impact loads in an abnormal operating environment (e.g., earthquake) or a loss-of-coolant accident (LOCA). Moreover, the spacer grid assembly must maintain the instrumentation tube straight so that a plant's neutronic instrumentation can be freely inserted and removed from the tube even after the lateral loading conditions have been exceeded. Therefore, a plastic deformation of a spacer grid assembly needs to be designed to have enough impact lateral strength [1].

Several studies have been devoted to the experiments, analyses and design of a spacer grid [2-7]. The design and material for a spacer grid and a design optimization of the outer plate in a space grid has been performed by considering the stiffness impact strength and the flow restriction [2, 3]. The buckling behavior is one of the important performances for evaluating the lateral strength,

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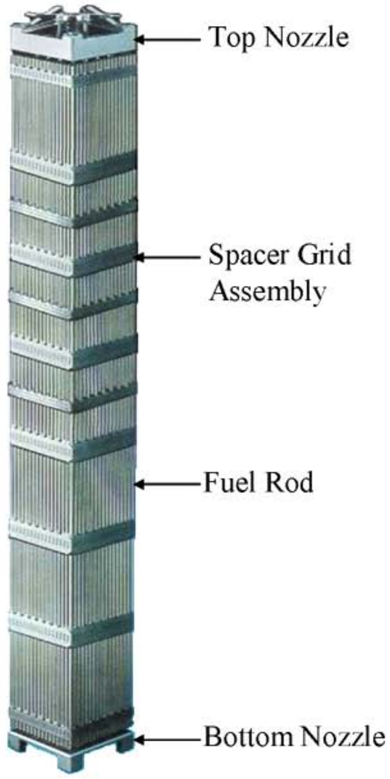
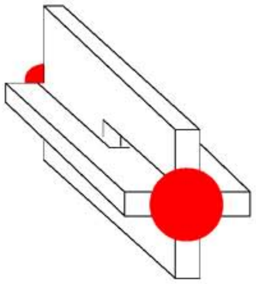
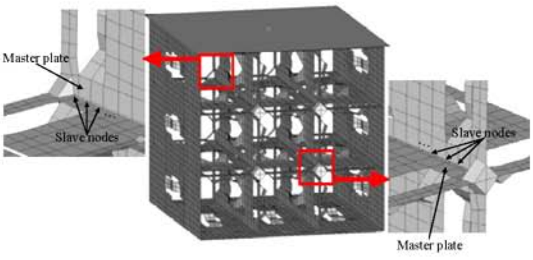


Fig. 1. PWR fuel assembly.



(a) Simplified view



(b) Enlarged view

Fig. 2. Detailed view at an intersection.

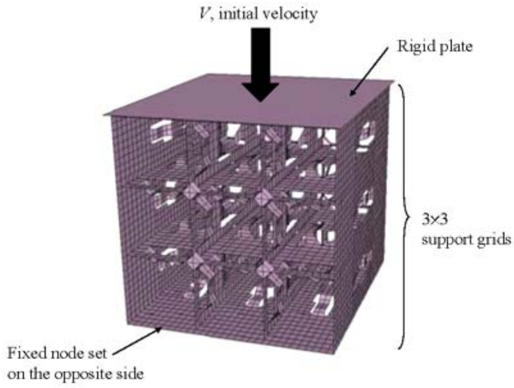


Fig. 3. Load and boundary conditions.

because the deformation of spacers needs to be limited to safely maintain the guide thimbles in an abnormal operating condition such as an earthquake [4, 5]. A finite element method for predicting the buckling behaviour on a spacer grid structure is established, reflecting a real test environment, by a commercial finite element (FE) code ABAQUS/Explicit [6]. An effort to improve the impact resistance of a support grid using an axiomatic design and optimization skills has been reported [7], where the dimple location and the welding penetration depth at the intersection of the grid has been studied and optimized. The lateral impact resistance has not been sufficiently studied rather than other functionalities such as an amount of fretting wear and heat transfer, even though it has much room for improvement [7].

The verified FE modeling technique through the foregoing research enabled the design optimization of the grid shape to improve the lateral impact strength. In this study, impact analyses are carried out on a spacer grid assembly. A finite element (FE) model of the spacer grid assembly is constructed and a nonlinear dynamic analysis is performed by using ABAQUS/Explicit. In general, an optimization process requires high computation cost, so a 3×3 model is chosen to facilitate fast computation. It is difficult to say that the optimization result from the 3×3 model can be directly applicable to a full size grid. But the strength of the full sized grid can be also attained by improving the strength for the unit strap or smaller sized grids [9]. The effect of a dimple location in a 3×3 support grid on its impact strength has been studied as a preliminary parameter study for a full sized support grid. The optimal location of the dimple has been found and some design guidelines for a support grid have been provided.

2. FE modeling

The FE modeling of the 3×3 spacer grid assembly has been done by interconnecting the slotted grid straps and welding at the intersections as shown in Fig. 2. The intersecting part is simply illustrated in Fig. 2(a), where the position of a spot weld is indicated as circles at both ends. In the FE model, six node solid elements are used to model the welding bead which shares the nodes with the shell elements, and contact conditions are applied along the intersecting slots (the enlarged subfigures in Fig. 2(b)); the two intersecting straps at 90 degrees do not interfere with each other. In this FE model, S3R, S4R shell elements and C3D6 solid elements in ABAQUS have been used: total 7246 nodes and 6070 elements.

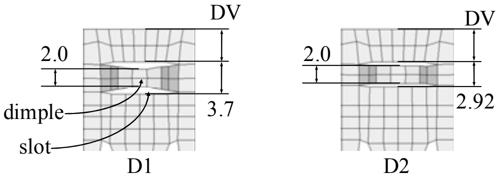
The FE analysis is constructed by considering a real impact experiment environment; an impact hammer is modeled as a rigid element with an equivalent mass, the contact condition is applied between the rigid plate and the support grids, and the nodes at the bottom plate are fixed as shown in Fig. 3. The initial impact velocity at the reference node (at the center of the upper rigid surface) is applied, and the output accelerations for the initial impact velocity are obtained at this node. The impact force of the grid is evaluated: multiplying the maximum acceleration of the model by the mass of the impact hammer. The impact analyses are done for different velocities from 381 mm/s and by an increasing increment of 63.5 mm/s. The impact force generally increases as the velocity increases, but for a certain case it decreases where the structure is considered to experience a buckling. The critical impact load is taken as the impact force from this case where the peak point is observed.

Since we are dealing with plastic buckling phenomena, the mechanical property of the material has to be considered by the elastic-plastic characteristic curve from the unidirectional tensile test according to the ASTM procedure [10]. The elastic-plastic material properties of Zircaloy-4 are used [8]

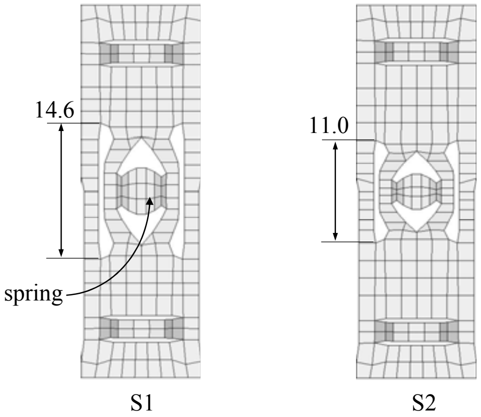
3. Parametric study

In this paper, four different kinds of the unit straps are considered where the dimensions of the central H-spring and the dimples vary as shown in Fig. 4, which are design change candidates already determined by the existing mold in a sheet metal machine. The dimple shape varies as the width of the horizontal slot differs while the central width of the dimple is fixed as 2.0 mm (type D1 and D2) as shown in Fig. 4(a). The H-spring is considered to have two different lengths (type S1 and S2) as shown in Fig. 4(b). Totally, we have four different combinations for the unit strap: D1-S1, D1-S2, D2-S1, and D2-S2. It is noted that the combination of D1-S1 is currently applied to the commercial spacer grid design. Each combination has the same node numbers and element connectivity.

For each combination, the task we would like to perform is a one-dimensional search with one design variable. Several algorithms for this search could be available, such as Amijo's rule or the Golden section method [11]. But they require a convergence criterion which may affect the convergence rate, or some of them need a sensitivity analysis which would require strict mathematical proof. Therefore, we choose a simple parametric study: to divide the design variable range into about 10 segments, and find the maximum critical impact load and the corresponding design variable.

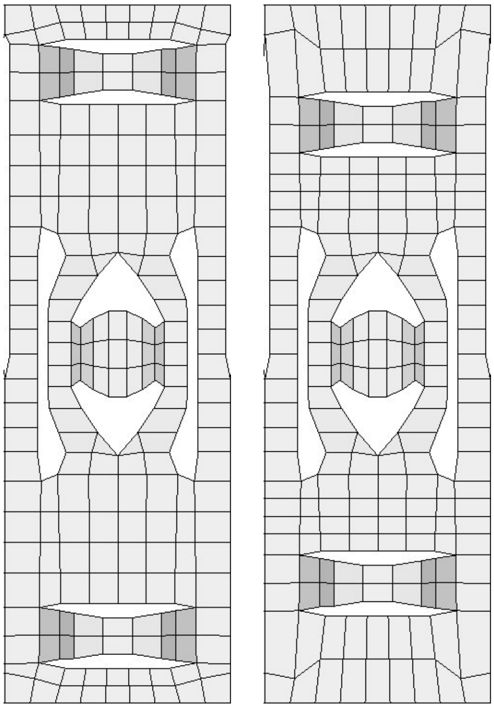


(a) Dimple and its slot



(b) Spring

Fig. 4. Dimple and spring settings.



(a) DV = 2.0 mm (b) DV = 5.0 mm

Fig. 5. Consistent mesh connectivity.

4. Data analysis

The design variable is chosen to be the location of the dimple, marked as "DV" in Fig. 4(a). We vary it from 2.0 mm to 5.0 mm in the increment of 0.25 mm and perform FE analysis for each setting to find the optimal position with the maximum critical load for all four combinations (D1-S1 to D2-S2). As DV changes, the node locations smoothly change to retain the mesh size evenly and maintain mesh connectivity. Fig. 5 shows the FE mesh for the D1-S1 case at DV = 2.0 and 5.0, respectively. In these figures, the nodes shared with the welding beads do not change their locations as well as the ones of the H-springs.

As explained in Section 2, the critical impact load is obtained at the first peak in an "impacting velocity-impact load" plot. For example, in the case of D1-S1 and DV = 3.5 as shown in Fig. 6, the critical load is 18.554 kN when the impacting velocity is 1016 mm/s (marked with a vertical dashed line in the chart). At this point, the deformation shape of the grid changes as shown in Fig. 6: the two outer vertical plates are parallel before the peak, but they deform symmetrically thereafter.

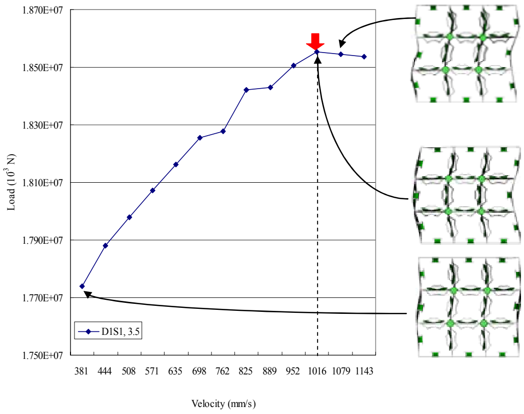


Fig. 6. Change of the deformation in the neighborhood of a critical load.

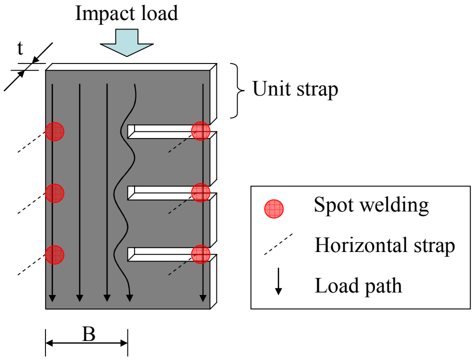


Fig. 7. Effective height of a strap.

The optimization results are summarized in Fig. 8 and Table 1. The maximum critical load has been discovered from the D2-S2 case and decreases in the order of D1-S2, D2-S1, and D1-S1. It is concluded that a smaller dimple slot (D2) and a shorter spring (S2) allocates more material "in-plane" of the strap and contributes to enduring a larger impact load. The optimal location of the dimple (DV) is around 3.5 ~ 3.75 mm for all of the combinations. It can also be shown that the spring shape is a far more significant factor rather than the configuration of the dimple: the difference of D1-S1~D1-S2 (+3.7%) is larger than that of D1-S1~D2-S1 (+1.5% in Table 1), for example. The maximum critical loads for the four configurations are marked by using a thick arrow in Fig. 8.

The crush strength of a support grid is strongly related to its buckling strength, as shown in Fig. 6; the critical impact load is observed when the grid experiences a buckling. Based on the fact that the critical load (P_{cr}) is proportional to the moment of inertia (I),

Table 1. Critical load for each configuration (kN) and the ratio for the D1-S1 case.

Dimple Spring	D1	D2
S1	18.568 (+0.0%)	18.843 (+1.5%)
S2	19.251 (+3.7%)	19.576 (+5.4%)

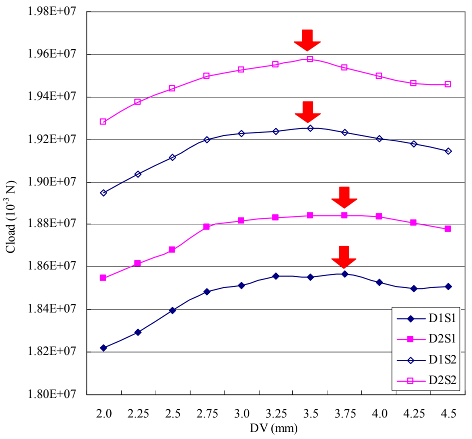


Fig. 8. Critical load with a change of the DV.

P_{cr} can be enlarged by increasing the plate thickness (t) and the artificial height (B) of the strap, as shown in Fig. 7. B refers the part in a strap where a load passes, which is smaller than the height of the strap. Fig. 7 shows a simple case where there are no dimples and springs, and we can improve P_{cr} by increasing B or reducing the gap length. Considering a real strap with a more complicated shape, however, it is very hard to say that P_{cr} can be improved just by reducing the gap length. At least we can suppose that the configurations of the smaller dimple slot (D2) and the shorter spring (S2) have a similar effect to enlarging B and facilitate the strength improvement. A closer examination of the finding of an obvious relationship between the crush strength and the strap shape remains as one of our future works, by taking the welding and the interconnecting conditions into account.

5. Conclusions

A parameter study for a dimple location in a 3×3 spacer grid under its critical impact load has been performed. Two different kinds of dimples and H-springs are considered and their effects on the critical load are also studied. We suggest setting the dimple location (DV) about 3.5 mm from the tip of the strap and allocating sufficient material in the plane of the strap by reducing the spring length and the dimple gap. We plan to apply the new design to larger size grids such as 7×7 or 16×16, manufacture and experimentally verify the new design to prove the strength performance. However, the dimple and the spring should be carefully designed to have enough stiffness for supporting the fuel rods, which is not considered in this work. The study of the 3×3 grid in this paper is a preliminary research and the results of this work should also be evaluated for a larger-sized grid which is used commercially in a plant.

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