Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July10-15, 2022
Division VI

EMBEDMENT DESIGN IN SAFETY-RELATED CONCRETE

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ABSTRACT

Embedment as specific designed anchorage assembly is buried in concrete performing as secured anchorage (connection) between concrete and supporting structure-system-component (SSC). Through this way, loads are transferred from SSCs to embedment, and then to concrete (base-line). So the analysis and design of embedment are very important to secure a robust support to SSCs. This paper is contributed primarily to develop standard designs for embedded plate assembly which will be used to support class 1 through 3 piping support attachment. The embedded plates (assembly) contained within this paper also have a generic application and may be used to support safety-related components including but not limited to: pipe supports, cabinets, cable trays, raceways, which may be attached to structural concrete through such an assembly. The analyses include axial, shear, and moment capacities with corresponding spacing requirements and plate flexibility information to support the design.

INTRODUCTION

The widely used embedment in concrete is a reliable and robust design for anchoring system, equipment and component to their base-line structures (normally the main structures). Without embedment the building structure cannot perform its functions to house all kinds of system, equipment, pipeline and component etc. In reality, embedment design mainly comprises of following assembly design which are buried in concrete: (1) embedded steel plate (include shear-lug), (2) anchor / stud and (3) base-layer concrete (include reinforcement). Following Figure 1 showed a brief flowchart of embedment design process.

Generally, the design method for embedment assembly is following the philosophy called “ductile design”. The basic mechanism of ductile design for embedment is focused on the aspect that the permissible failure of embedment assembly is only from the plastic failure of stud / or anchor; the concrete (also called as “concrete cone”), due to its brittle nature, have to be excluded from the failure mode. So in design practices, the buried depth, the spacing, the edge distance of stud are carefully considered to ensure that the whole embedment assembly is designed in a reliable and robust way to support the SSCs as described above. In the engineering design of Safety-Related embedment, additional (special) rules are set forth to comply with certain safety-related design criteria (also called “safety functions”), such as seismic category-I nuclear concrete (ACI code), Class 1 through Class 3 for safety-related pipe support (ASME III code) etc. All these codes give design requirements regarding a critical safety state called Safe Shutdown Earthquake (SSE), hence SSE is also called design-basis for above safety-related SSCs and their supports in a facility.

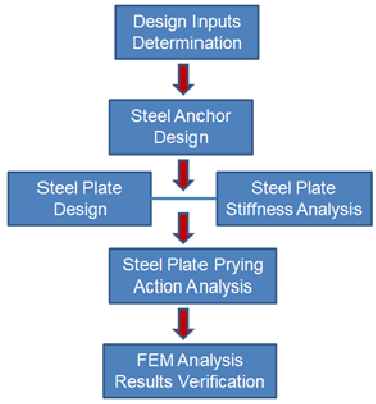


Figure 1 Flow chart of embedment design process

The purpose of this research is to provide new approach for balance-of-plant (BOP) engineers to let them fully understand the essential parts of embedment design. Second, this paper can also serve as the channel for experienced BOP engineers to let them have a systematic mastering on improved embedment design based on ACI code. Further, as the results this paper revealed the relationship between embedment standard design and detail design, so through this way, the complicated embedment design can be greatly simplified; the design processes and results interpretation could be more meaningful and useful for detail design phase and construction phase.

DESIGN METHOD BASED ON AMERICAN CODES / STANDARDS

The Design Basis

- Design codes / standards

The design of safety-related embedment for supporting SSCs shall be performed in accordance with the governing ACI, AISC and ASME codes and specifications shown as following:

(1) "Code Requirements for Nuclear Safety Related Concrete Structures and Commentary" ACI 3491
(2) "Guide to the Concrete Capacity Design (CCD) Method—Embedment Design Examples" ACI 349.2R 2
(3) "Specification for the Design, Fabrication, and Erection of Steel Safety Related Structures for Nuclear Facilities" AISC N6903
(4) "Rules for Construction of Nuclear Facility Components" ASME SECTION III, Div.2 - "Code for Concrete Containments"4
(5) "Structural Welding Code –Steel", D-1.1/D1.1M5

- Design criteria

The design of safety-related embedment should be performed based on the design criteria given below:

(i) The embedded plate and shear-lug will be designed in accordance with the allowable stress design （ASD）based on AISC N690.
(ii) The concrete embedment will be designed in accordance with the ultimate Concrete Capacity Design (CCD) requirements of ACI 349.
(iii) The forces and moments applied to the plate are irrespective of direction, provided the design resultants are not exceeded.

Following assumptions are also used as the additional design criteria for embedment design:

(iv) Non-reinforced concrete properties are assumed in the design of the embedment. Reinforcement such as hair-pins are used in some cases to increase anchorage capacity in case the spacing / embedded depth / edge distance are in a constrained condition
(v) The embedment plate design is based on the loads applied concentrically to the center of the plate. Loads / moments can be applied in any direction (i.e. +/- loading conditions).
(vi) Shear-lugs are considered as part of the embedded plate configuration, and designed to resist the total applied shear load assuming there is no contribution / interaction from the embedded studs

The Design Principles

The design of safety-related embedment shall be conducted in accordance with following principles given in governing ACI, AISC and ASME codes:

(a) The design method for embedment as a whole is following the philosophy called "ductile design".
(b) The design of the embedded element considers the orientation and location of the loads. When multiple values are provided, the worst case will be used as the enveloped load. The design input values include but not limited to: embedment depth, anchor-to-anchor spacing, anchor-to-edge spacing, plate size and thickness and stud / plate stiffness.
(c) The embedded plate and its flexibility are designed in accordance with the Allowable Stress Design (ASD) methodology outlined in AISC N690. The applicable factored load is applied to the embedded plate and the resulting stresses and interaction are maintained within the elastic range of the steel plate. The applied factored loads are combined regardless of sign to create a symmetrical embedment to simplify field implementation.
(d) The buried anchors are designed to ultimate capacity (AISC plastic design) ; therefore, the actual loading still need to consider the appropriate load factors by following the rules given in item (vi) below.
(e) Because of the differences in the steel and concrete codes, the steel parts meet the requirements of the steel code, the base-layer concrete meet the requirements of the concrete code. But as a whole the working condition and ultimate condition of embedment assembly are controlled by principles outlined previously.
(f) As a general rule, if the applied load combination includes Safe Shutdown Earthquake (SSE) load, the applied load factor is 1.0; if the applied load combination does not include SSE load, then the applied loads will need to be increased based on corresponding code's requirements.

The Design Analysis Methods

Total embedment design-analysis follows designated basis, criteria and principles given previously, configurative physical model (mechanical model) need to be built to analyze embedment assembly together with the base-line concrete (concrete cone). To further reveal the plate and stud stiffness and corresponding deformations, finite element method (FEM) is utilized to create FE model to carry out detailed numerical analysis on plate flexibility and stud-concrete compressive contact action analysis.

- Material specification

Embedment plate, shear lug and stud / or anchor are code designated steel materials with the considerations on required properties such as stiffness / toughness, anti-corrosion and weldability etc. Following Table 1 showed some state-of-the-practice for material selection.

Table 1– Embedment assembly material selections (Example)

Material	Fy	Fu	Elastic Modulus	ASTM
	ksi (MPa)	ksi (MPa)	ksi (GPa)	Designation
Plate	50 (345)	65 (448)	29000 (200)	A529 or A572
Anchor / Stud	50 (345)	65 (448)	29000 (200)	A108
Electrode	E70xx or Equivalent			

- Load transfer and embedment design input load determination

The design loads on the embedment come from the SSCs supports: for instance, they may come from platform / frame, equipment, component and system etc. All these SSCs loads (as external loads to embedment) are transferred to embedment through attachments (attached members), the transferring locations are at the interface between steel plate and attachment member ends. Since this load transferring configuration is very similar to a typical column-floor connection, often time we called this type of load "footprint load" which is shown in Figure 2. Flowchart in Figure 3 showed the steps how to determine the design input loads for design.

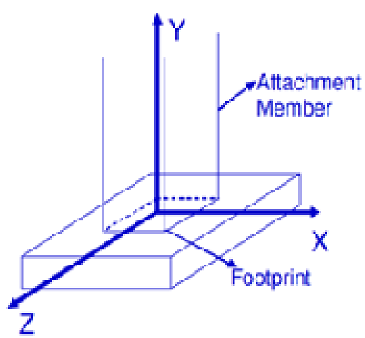


Figure 2 Load transferring and footprint load

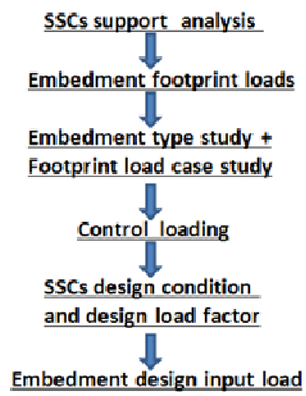


Figure 3 Embedment design load determination

- Steel design

Apart from base-line concrete, embedment design primarily is steel design, thus it follows current steel codes / standards. For non-safety-related SSCs, AISC ASD/LRFD is applicable; for safety-related, AISC N-690 is the mandatory code to be used. Following Table 2 is a brief summary of some steel design requirements that are applicable for safety-related embedment design.

Table 2 – Design allowable stresses for plate

Load Conditions	Allowable plate bending stress	Allowable plate tensile stress	Allowable plate shear stress
Normal / Severe	F_b=0.75F_y	F_t=0.60F_y	F_y=0.40F_y
F_y : Plate material minimum yield strength			

- Load group classification

Due to many types and the large number of embedment plates used for supporting SSCs, the individual plate loadings have to be divided into some load groups in order to simplify plate type selection and the determination of design input loadings. Following Table 3 showed ways of load group classification regarding of selected power struts (for example): these struts serve as the major pipe support members for piping systems in the nuclear power industry.

- Design load case determination (enveloped)

Previous Figure 3 gives the overall steps for determining the design input loadings to the embedment. Based on the classification in Table 3, an enveloped (controlling) case will be selected from the table to represent maximum input loads from certain load groups to simplify analysis process, For example, by comparison of individual input forces / moments and footprint sizes, "load group 5" condition can be selected as the controlling design condition to represent the load groups of 1 to 5 and 12. This means if engineer took "load group 5" design condition as the enveloped load case, the design outputs can be used for covering load group 1 to 5 and 12 respectively. Similar method can also be used to handle rest of the load groups in this table.

Table 3 – Load groups and support load capacities of "Bergen Power struts"

Load Group	F_v Kips (KN)	M_v Kip-ft (KN-m)	Footprint Size in. (mm)
1	0.7 (3.1)	0.1 (0.14)	1.5 x 1.5 (38x38)
2	1.5 (6.7)	0.3 (0.41)	2.0 x 2.0 (51x51)
3	4.0 (17.8)	0.8 (1.08)	2.0 x 2.0 (51x51)
4	7.0 (31.1)	1.7 (2.30)	3.5 x 3.5 (89x89)
5	12.0 (53.4)	2.9 (3.93)	3.5 x 3.5 (89x89)
6	25.0 (111.2)	8.1 (10.98)	5.0 x 5.0 (127x127)
7	35.0 (155.7)	12.4 (16.81)	6.0 x 6.0 (152x152)
8	60.0 (267)	28.2 (38.23)	7.5 x 7.5 (191x191)
9	80.0 (355.8)	41.7 (56.54)	9.5 x 9.5 (241x241)
10	130.0 (578.2)	92.1 (124.87)	12 x 12 (305x305)
11	200.0 (889.6)	179.2 (242.96)	12 x 12 (305x305)
12	1.0 (4.4)	3.0 (4.07)	2.0 x 2.0 (51x51)
13	5.0 (22.2)	15.0 (20.34)	4.0 x 4.0 (102x102)
14	10.0 (44.5)	30.0 (40.67)	4.0 x 4.0 (102x102)
15	20.0 (89.0)	60.0 (81.35)	8.0 x 8.0 (203x203)
16	50.0 (222.4)	150.0 (203.37)	12.0 x 12.0 (305x305)

Note: F_v and M_v are the resulting footprint loads for each load group.

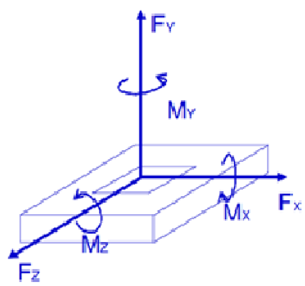
SAFETY-RELATED EMBEDMENT DESIGN EXAMPLE (By Referencing American Codes)

The Determination of Example Design Input Loads

Based on the discussion in previous sections, the design input loads can be determined based on the footprint loads of "load group 5" as shown in Table 4, and should apply on the embedment plate in a manner shown in Figure 4

Table 4 – Determination of enveloped load case

Load Group	Force Vector kips (KN)	Moment Vector kip-ft (KN-m)	Footprint Size in. (mm)
1	0.7 (3.1)	0.1 (0.14)	1.5 x 1.5 (38x38)
2	1.5 (6.7)	0.3 (0.41)	2.0 x 2.0 (51x51)
3	4.0 (17.8)	0.8 (1.08)	2.0 x 2.0 (51x51)
4	7.0 (31.1)	1.7 (2.30)	3.5 x 3.5 (89x89)
5	12.0 (53.4)	2.9 (3.93)	3.5 x 3.5 (89x89)
12	1.0 (4.4)	3.0 (4.07)	2.0 x 2.0 (51x51)



F_X= 12.0 kips (53.4 KN)
F_Y= 12.0 kips (53.4 KN)
F_Z= 12.0 kips (53.4 KN)

M_X= 2.9 kip-ft (3.93 KN-m)
M_Y= 2.9 kip-ft (3.93 KN-m)
M_Z= 2.9 kip-ft (3.93 KN-m)

Figure 4 Design input loads determined for designated embedment plates (1 to 5 and 12)

Consideration of Load Factors

Just as described in previous sections, a complete embedment comprises of the steel assembly part (which includes plate, shear-lug, stud/anchor) and the concrete portion (which serves as the base-layer medium to anchor the steel assembly). For safety-related SSC support, the steel plates are designed using the Allowable Stress Design provisions as identified in AISC N690; meanwhile the base-layer concrete and buried stud / anchor design are following the Strength Design / or Plastic Design requirements given in ACI 349 and LRFD method. So the embedment failure is controlled by the plastic yielding of stud / or anchor; the design input loading determination should consider appropriate load factors which should comply with strength design method.

Embedment Plate Design

Typically, the plate is designed for the attachment (weldment) to be placed approximately at the center of the plate with the assumption that the location is bounded by a geometric perimeter described by the anchors in Figure 5. The example in this paper is provided to demonstrate an analytical method which can be used to design steel plate through a hand-calculation approach. The plate is designed using the Allowable Stress Design methodology as identified in AISC N690. Calculation results will be compared to finite element analysis results from computer software.

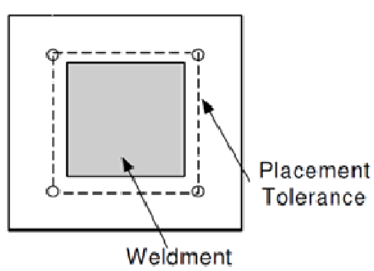


Figure 5 Typical embedded plate with attachment

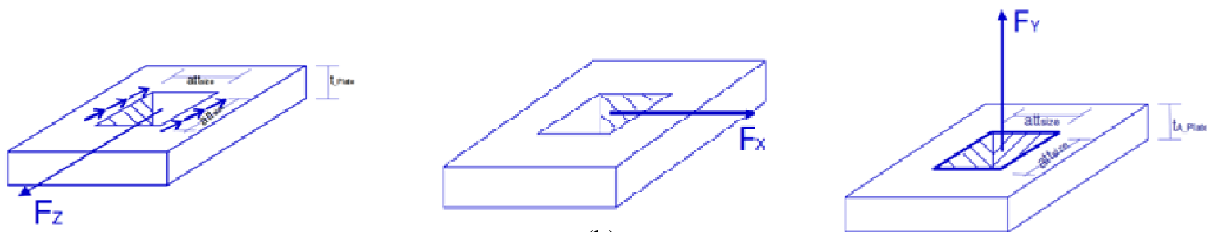
- Shear capacity of steel plate

The shear capacity (in-plane) of selected plate needs to be evaluated based on the design input loads and the size of footprint shown in Figure 4 and Table 5. It is assumed that plate shear effects due to torsion are neglected. Plate will never fail prior to anchor, that means failure mode is controlled by anchor (stud). The design input loads (force vector and moment vector) from Table 4 will be applied at X, Y, Z directions individually, assuming they are the maximum input force and moment in that direction.

Table 5 – The Design Dimensions of Selected Plate

Design Dimensions in inch (mm)	Plate Length	Plate Width	Plate Thickness	Attachment Size
	8.0 (203)	8.0 (203)	0.75 (19)	3.5 (89)

Figure 6 (a) (b) (c) showed the typical in-plane and out-of-plane rupture shear hand-calculation models for the plate.



(a) (b) (c)

Figure 6 Shear rupture calculation models for the selected plate

Table 6 showed additional criteria for the plate's rupture shear. The plate rupture shear capacities are adequate if they are all greater than the resulting shear forces due to the design input loads. One thing needs to keep in mind is that the shear capacity of whole embedment shall be controlled by steel anchors or shear-lugs (it is not controlled by plate).

Table 6 – The Design Allowable Stresses of Plate (with Rupture Shear)

Load Conditions	Allowable Plate Bending Stress	Allowable Plate Tensile Stress	Allowable Plate Shear Stress (Direct Shear)	Allowable Plate Shear Stress (Rupture Shear)
Normal / Severe	F_b=0.75F_y	F_t=0.6F_y	F_v=0.4F_y	F_{vr}=0.3F_u

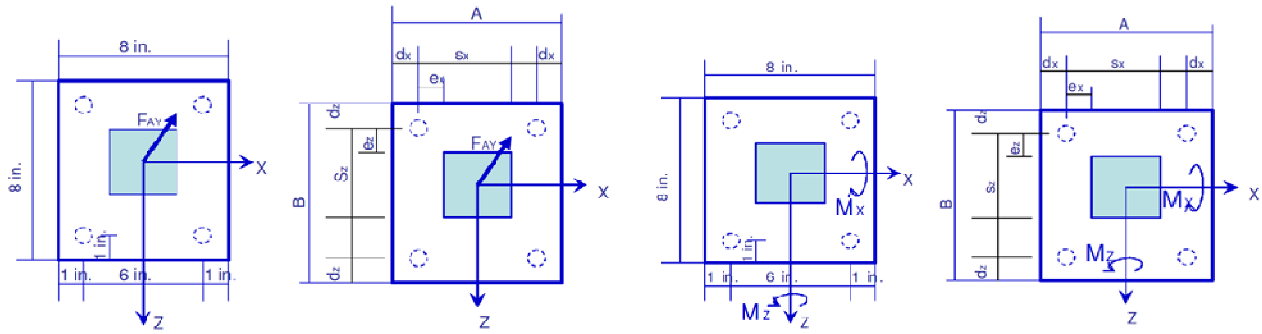
Note: F_y : Minimum Yield Strength of Plate
F_u : Minimum Tensile Strength of Plate

- Plate local bending capacity due to applied tensile force

Tension load Fy (vertical to the plate) results in local bending on the plate at the location of the attached member. Affected by stud arrangement, attachment size, and eccentricity of attached member, such local bending can be critical to the plate, and needs to be checked. Following Figure 7 (a) (b) showed stud arrangement, attachment size and other terms related to plate local bending evaluations.

- Plate local bending capacity due to applied moment

Similarly concentrated global moments applied on plate also result in local bending on the plate at the location of faces of attachment member. Affected by stud arrangement, attachment size and eccentricity of attachment member, the local bending can be critical to the plate, thus needs to be checked with similar method (Figure 7 (c), (d)) used for above tensile load.



(a) (b) (c) (d)

Figure 7 Plate local bending due to applied tensile forces and moments

- Check bending capacity of plate through the combination of load effects

Since the applied external force (Fy) and moments (Mx, Mz) could result in several similar load effects at orthogonal directions (e.g. X and Z directions here) on the plate, the ratio of "maximum combined stresses" to "allowable stress" shall be checked.

- **E/PD Strudl** finite element analysis (FEA) versus hand-calculations

Embedment plate design can also be carried out by using designated computational software such as E/PD Strudl etc. Due to the contents limitation in this paper, the application of FEA for embedment analysis is out of the scope of this paper. Following Table 7 is a summary of the comparisons between FEA and hand-calculation. As we well known in nuclear power industry, all safety-related design through computational software / tools should also be verified by valid analytical method (such as hand-calculation). From the comparisons in Table 7, hand-calculation results are close to E/PD Strudl finite element analysis results. The hand-calculations give conservative results because the flexibility of the plate and the concrete contact-reaction are ignored.

Table 7 – Hand calculation versus E/PD Strudl analysis

Analysis Method	**Tensile Force Applied**		**Moment Applied**	
	f_{bx} ksi (Mpa)	**f_{bz} ksi (Mpa)**	**f_{bx} ksi (Mpa)**	**f_{bz} ksi (Mpa)**
Hand Calculation	10.0 (68.9)	10.0 (68.9)	12.21 (84.2)	12.21 (84.2)
E/PD Strudl FEM	9.25 (63.8)	9.25 (63.8)	11.41 (78.7)	11.41 (78.7)

Embedded anchor (stud) Design

Embedded anchors (studs) design shall be fully in accordance with ACI 349 on following aspects:

(1) Concrete breakout strength in tension
(2) Pullout strength in tension
(3) Concrete side face blowout strength in tension
(4) Steel shear strength
(5) Concrete breakout strength in shear
(6) Pry-out strength in shear
(7) Tension-shear interaction of anchor (stud)

Design Interaction Final Checks for Embedment Assembly

The embedment assembly as a whole may be subjected to combined loading conditions consisting of axial, shear, and moments, as such it should be checked by following the similar criteria given in ACI 349-13 Appendix D7 and its commentaries. However, in actual design, large shear loads may be encountered which require the uses of shear-lug to be included in the design of the embedded plate. If shear-lug is included in the design of steel plate, the lugs usually are designed to resist the full shear loading and the anchors then designed for tension only (resist the pullout force only). For design purposes, the steel plate interaction ratios are computed based on the following recommended formula to comply with ACI 349-13 Appendix D7 requirements:

- When there is no shear-lug used, the following interaction equation shall be satisfied:

$$\underbrace{\left(\frac{F_y}{F_{capacity}}+\frac{M_x}{M_{capacity}}+\frac{M_y}{M_{capacity}}\right)^{\frac{5}{3}}}_{\text{(Tensile)}}+\underbrace{\left[\sqrt{\left(\frac{F_x}{F_{capacity}}\right)^2+\left(\frac{F_z}{F_{capacity}}\right)^2}\right]^{\frac{5}{3}}}_{\text{(Shear)}}\leq 1.2 \tag{1}$$

- Where shear lugs exist, the design is performed based on vector forces and moments. The following interaction equation shall be satisfied:

$$\left(\frac{F_{actual}}{F_{capacity}}\right)+\left(\frac{M_{actual}}{M_{capacity}}\right)\leq 1.0 \tag{2}$$

NOMENCLATURE:

The following symbols are used in the paper:
Sx : Distance from center of studs to far face of attachment along X axis
ex : Distance from center of studs to near face of attachment along X axis
Sz : Distance from center of studs to far face of attachment along Z axis
ez : Distance from center of studs to near face of attachment along Z axis
Factual and M actual = Actual loads calculated as vectors.
M_x, M_y, F_x, F_y and F_z = Actual loads calculated as components.
$F_{capacity}$ and $M_{capacity}$ = Embedment plate maximum capacities (ultimate strength) based on design.

APPLICATION DISCUSSION

(1) Embedment design, as the downstream structural work in safety-related SSC design, primarily considers the accommodation of supporting attachments and secures all loads into the base-layer concrete. Due to the large number of embedment plate, schedule-wise speaking it is critical to some engineering scopes such as "Balance of Plant" (BOP); hence the execution and completion of embedment design in an efficient and effective way have great impact to the works of whole plant.

(2) Even though the design principles, methods and procedures recommended in this paper are focused on the supports of safety-related SSCs (which basically are plant secondary structures anchored in the baseline of main-structures), these rules can also be used for non-safety-related SSCs, and even other generic civil works, provided the related code/standard requirements comply with each other.

(3) The embedment assembly as a whole is comprised of steel plate, welded anchors / studs and the surrounding concrete block for anchorage. The designed failure mode for the embedment is ductile failure of anchors / studs; concrete due to its brittle behaviour is designed to be excluded from any failure modes (all code's checks investigated on breakouts and blowouts etc. are intended to prevent such failures).

(4) The embedded plate and its flexibility are designed in accordance with the Allowable Stress Design (ASD) method outlined in AISC N690. The applicable factored loads are applied to the embedded plate; the resulting stresses and interactions are maintained within the elastic range of the steel plate.

The applied factored loads are combined regardless of sign to create a symmetrical embedment to simplify construction.

(5) The anchors /studs are designed to ultimate capacity (steel plastic design); therefore, the actual loadings for anchor design also need to consider appropriate load factors as dictated by the AISC code.

(6) The concrete embedment block will be designed in accordance with the ultimate Concrete Capacity Design (CCD) requirements outlined in ACI 349.

(7) As a general rule, if the applied load combination includes Safe Shutdown Earthquake (SSE) load, the applied load factor is taken as 1.0 for all loads; otherwise, the applied loads will need to be increased based on load factors that is defined in corresponding code requirements. For simplicity and conservatism, an enveloped load factor value of 1.5 - 1.7 can be used for the embedment system design.

(8) Apart from the design of embedment capacities, the stiffness evaluation of embedment assembly is also important for deformation control and serviceability. The stiffness of anchor / stud often time can be easily obtained from vendor's products manual or determined by testing; meanwhile the stiffness of steel plate (especially for flexible plate) is hard to determine through a simple approach. The best design practice is the utilization of finite element analysis method and tools to accurately evaluate plate stiffness subjected to forces and moments. This becomes the future topics to be further investigated.

(9) The application of FEM software plus design automation tools on embedment system design can greatly facilitate the design process, increase accuracy, bridge the gap of interface and save engineering cost.

(10) As one important conclusion at the last: "standard design" can be used to serve as a batch-processing-tool for handling complicated engineering works which often times related to large number of design tasks and series of design process. By the way of "standard design", large number of actual design cases are greatly reduced and simplified to (limited) typical design cases. Solutions provided for typical cases can play as reference boundaries to give solutions to all individual embedment plate in detail design.

CONCLUSION

This paper is contributed primarily to develop standard designs procedures for embedded plate assembly which is used to support class 1 through 3 piping support attachment. The embedded plates (assembly) contained within this paper can also have a generic application and may be used to support other safety-related components including but not limited to: equipment, cable trays / raceway and cabinet etc. The analyses include axial, shear, and moment capacities with corresponding spacing requirements and plate flexibility information to support the design.

REFERENCES

American Concrete Institute. *ACI 349-13 "Code Requirements for Nuclear Safety-Related Concrete Structures and Commentary".* USA, 2014.

ACI 349.2R-07. *"Guide to the Concrete Capacity Design (CCD) Method - Embedment Design Examples".* Reported by ACI Committee 349, 2007.

AISC N690-1994 (R 2004). *"Specification for the Design, Fabrication, and Erection of Steel Safety Related Structures for Nuclear Facilities"* with Supplement 2. dated October 6, 2004.

ASME Section III Division 2 *"Code for Concrete Containments".* BPVC.III, USA Feb. 2017.

American Welding Society. *Structural Welding Code -Steel, D-1.1/D1.1M.* USA 2006.

Design Data Nelson Concrete Anchor. Studs *for Securing Steel to Concrete, Design Manual #21.*

Phi-Delta, Inc. *E/PD Strudl Computer Program. Version 0707.*

Galunic, B. (1980) *"Procedure for Calculating Forces in Concrete Anchors Considering The Flexibility of The Support"*, Prepared for Public Service Electric & Gas Company.