24th INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
23–27 July 2017, London

WIND-RESISTANT AND SEISMIC DESIGN OF THIRD GENERATION NUCLEAR POWER ENGINEERING VNA SYSTEM

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Aiming at the towering structure VNA (Very Narrow Aisles) system (50m or so height) this paper completes the standards-compliant design and mechanical calculation of wind-resistant and seismic. Using of composite material mechanics theory to set distribution ratio and design the layer of the pipe body. It includes glass fibre and vinyl ester resin as the basic raw material. It meets the design specifications book about the basic mechanical requirements of tensile strength, flexural strength, shear strength and resistance pulling modulus, bending modulus. According to the design specifications for VNA system wind calculation, it includes two conditions: a once-in-a-century great wind speed and tornado. Using ANSYS WORKBENCH large general-purpose finite element analysis software for FSI (Fluid Structure Interaction) calculation. According to the seismic design specification requirements, using finite element analysis software to calculate the structure response spectra by using of local OBE (Operating-Basis Earthquake) and SSE (Safety Shutdown Earthquake) seismic response spectrum. According to the requirements of design specification for calculating the working condition, this paper combines each physical field analysis module. By design and calculations, according to the requirements and the actual situation, the main bearing member of the VNA system was focused on the design and optimization. In this paper, dynamic design and finite element method provide the effective technical support and engineering application reference for VNA ventilation chimneys of the three generations nuclear power island and tall buildings in wind-resistant and seismic design.
Keywords: VNA system; Tall structures; Wind-resistant and seismic; Finite element

1. Introduction

VNA system as the exhaust chimney equipment of the third generation nuclear power plant and the last link of ensuring radiation protection barrier should also satisfy the requirements of the third-generation nuclear power technology: maturity, security and economy. In terms of security, VNA system should have a high level of wind-resistant and seismic performance. Gale is a fast-flowing air and wind power on layer near the ground up to magnitude eight or higher. The wind will destroy the ground facilities and buildings. It has great harm, and is a kind of severe weather [1-4]. A tornado is a small regional scale atmospheric vortex with violently rotating, it is sudden, strong, disappearing fast and ferocious. It is a large severe weather, extremely destructive. The tornado through the place, often resulting in the phenomenon of the building destructed [5-8]. Practice shows that casualties and economic losses are caused by the devastating earthquake, mainly due to the huge energy generated when an earthquake makes buildings and engineering facilities to be destructed and collapsed, as well as accompanying secondary disasters. And this energy collision occurred mainly between the ground and the structure; one structure and the others [9-12]. The energy collisions between the nuclear islands and VNA system is a problem that must be considered in the design because of VNA system as the adhesion towering buildings. VNA system must be able to withstand wind loads of hundred years, tornadoes load and seismic loads, even these types of normative loads combined.

Based on one design condition (self-weight + annex-weight + OBE seismic load + a once-in-a-century great wind speed) and two types of accident conditions (self-weight + annex-weight + tornado wind load; self-weight + annex-weight + SSE seismic load), calculation results were analyzed. According to the appropriate level of specification, mechanical support parts, steel parts and bolt fasteners are checked; according to the design standards the mechanical index subject of the chimney pipe are checked. By assessing the results of the check, trying to adjust the pipeline ply design, select universally applicable higher-grade steel, and attempting to change the structure design so that all parts reach the design criteria. Adopting a variety of ways to reduce reaction force of the APC shell to improve the safety of the outside wall of the nuclear island. This paper provides effective technical support and engineering application reference in wind-resistant and seismic design for VNA exhaust chimney of the third-generation nuclear power plant and the general towering buildings.

2. Numerical simulation model

2.1 FRP layer design

FRP pipe includes glass fibres and vinyl ester resin as the basic raw material. When winding, reinforcements and the base material percentage ratio of the pipeline structure layer composite material are controlled as follows, in which that W_f represents the glass fibres weight fraction, W_m represents the resin matrix weight fraction, V_f represents glass fibre volume fraction, V_m represents the resin matrix volume fraction.

Table 1: The percentage and design parameters of material

Variate	Glass fibres	Resin matrix
Tensile strength (MPa)	σ_{ft}=1000	σ_{mt}=65
Elastic modulus (MPa)	E_f=7000	E_m=3500
Poisson's ratio	ν_f=0.3	ν_m=0.35
Density (kg/m3)	ρ_f=2540	ρ_m=1200
Shear modulus (MPa)	G_f=26923	G_m=1296
Weight fraction	W_f=0.7	W_m=0.3
Volume fraction	V_f=0.524	V_m=0.476

According to the above material properties and the ratio, the design uses mechanical properties of the unidirectional positive axis plate FRP pipe (diameter is 3000mm) layer adopts combination of orthogonal winding layer and to toroidal winding layer. Through the composite material mechanics knowledge can get the mechanics performance of each basic layer as table 2.

Table 2: Basic layer mechanics performance

Variate	toroidal winding layer	orthogonal winding layer
Yarn sheet	40 sheaf × Tex4800	40 sheaf × Tex2400
Winding angle	88 °	±45 °
Thickness of single layer	0.72mm	1.02mm
Hoop tensile strength (MPa)	552.2	276.45
Axial tensile strength (MPa)	65	276.45
Hoop elastic modulus (MPa)	38369	13577

Axial elastic modulus (MPa)	12773	13577
Principal Poisson's ratio	0.32	0.4
In-plane shear modulus (MPa)	4832	11407

In the layer of horizontal pipe, hoop winding and orthogonal winding are alternated (13 hoop layers and 4 orthogonal layers). The overlay layer of the horizontal pipe structure is: 2 hoop layers/ 1 orthogonal layer / 3 hoop layers / 1orthogonal layers / 3 hoop layers / 1orthogonal layer / 3 1ayers hoop / 1orthogonal layer / 2 hoop layers. So mechanics performance of the horizontal pipe could be got, thickness of the horizontal pipe is 13.44mm, hoop tensile strength is 468.49MPa, axial tensile strength is 125.71MPa, inter laminar shear strength is 60MPa, hoop Elastic modulus is 30.84GPa, axial Elastic modulus is 13.02GPa, Poisson's ratio is 0.34 and in-plane shear modulus is 6.828GPa.

Because of the vertical pipe suffered major loads, in order to ensure the mechanical properties of pipeline, in the structural design of different thickness, this paper has designed different plies in the actual winding process. And in order to ensure the continuity of entangled fibres, some layers could consider hand layup with contacting ply moulding method. In table 3, T_d represents the design thickness, N_1 represents the hoop layer number, N_2 represents the orthogonal layer number, T_a represents the actual thickness, σ_a represents the axial tensile strength, σ_h represents the hoop tensile strength, μ represents the Poisson's ratio, G represents the shear modulus, E_h represents the hoop elastic modulus, E_a represents the axial elastic modulus.

Table 3: Vertical pipe overlay design results

T_d (mm)	8	14	18	20	21	22	24	26	28
N_1	5	8	11	12	12	13	15	16	16
N_2	4	8	10	11	12	12	13	14	16
T_a	7.68	13.92	18.12	19.86	20.88	21.60	24.06	25.80	27.84
σ_a (MPa)	177.33	188.95	184.03	184.46	188.95	184.82	181.53	182.04	188.95
σ_h (MPa)	405.71	390.55	396.98	396.41	390.55	395.94	400.23	399.58	390.55
μ	0.36	0.37	0.37	0.37	0.37	0.37	0.36	0.36	0.37
G (MPa)	8.32	8.69	8.53	8.55	8.69	8.56	8.46	8.47	8.69
E_h (MPa)	13.20	13.24	13.23	13.23	13.24	13.23	13.22	13.22	13.24
E_a (MPa)	25.20	23.84	24.41	24.36	23.84	24.32	24.70	24.65	23.84

In the design of vertical pipe layer, the axial tensile strength and the tensile modulus are given priority, and to optimize layer number and thickness. At the same time all pipe brackets use steel grade Q345C suggested.

2.2 Simulation model

VNA chimney exhaust system mainly consists of the pipeline, steel platform, mounting bracket, guide bracket, flow meter and lightning protection devices and other components. Based on the actual situation, the finite element model of the VNA system is shown in Figure 1.

The model includes Φ3000mm reinforced composite pipe; Φ400mm long-thin composite pipe; saddle supports of horizontal pipe (five sets); guide brackets of vertical pipe (five sets); platform surface (two); meter platform; access platform; brackets of Φ400mm composite pipe (six sets); mounting support bracket of vertical pipe (one); combined steel structure (one set); diagonal bar(four); polyurethane foam rings(nine) and EPDM damping rings, 160998 elements totally. Depending on the actual contact cases between the different structure, respectively using co-node, creating contact element, freedom coupling and other means for assembly.

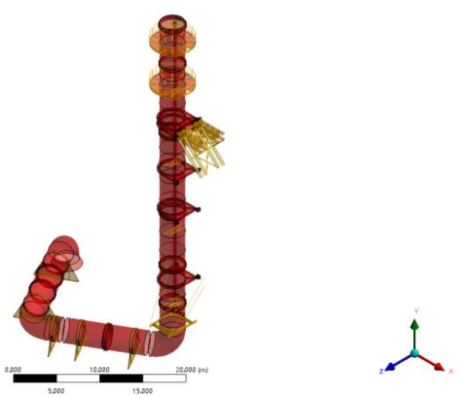

Figure 1(a): Structure model.

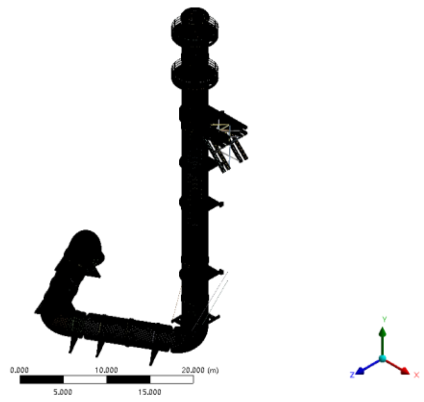

Figure 1(b): Finite element model.

To simulate this real problem as far as possible, considering the time-consuming and precision, this paper establishes a sufficiently large wind farm (200m $\times$ 200m $\times$ 100m) contained VNA system and its surrounding buildings (nuclear island and auxiliary plant). The flow field model is divided by 4852350 three-dimensional elements. To get the chimney surface pressure distribution, to provide accurate load data for the structural strength, stiffness and stability simulation under wind loads. Wherein the CFD model is shown in Figure 2.

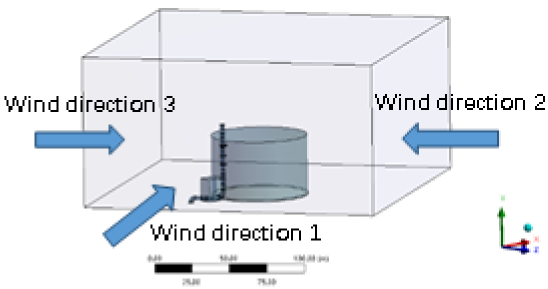

Figure 2(a): CFD numerical model.

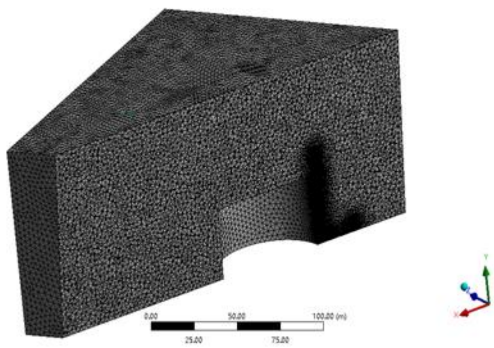

Figure 2(b): Section Plane of finite element model.

2.3 Solving settings and methods

This paper using CFX on flow field analysis and researches effect respectively three typical direction blowing wind load on the VNA system (as shown in figure 2(a)).

In the figure 2(a), the arrow pointing in the model is inlet, its direction parallel to the face normal. Bottom surface is the wall boundary. The rest four face are opening boundary. Nuclear and pipeline surfaces are wall boundary. And boundary settings as follows: 1) Inlet flow regime is subsonic, normal speed is exponential wind profile u(y) (a once-in-a-century great wind) or 71.4m/s (tornado design basis speed), mass and momentum is normal speed, turbulence is medium intensity and eddy viscosity ratio. 2) Opening flow direction is normal to boundary condition, flow regime is subsonic, mass and momentum is opening pressure and direction, relative pressure is 0Pa, turbulence is medium intensity and eddy viscosity ratio. 3) Wall influence on flow is no slip. Considering the flow velocity and Reynolds number, turbulence model is adopted in the shear stress transport, calculation accuracy is high resolution, parameters of CFX database provides 25℃ air.

$$u(y) = 68.4\left(\frac{y}{10}\right)^{0.15}. \tag{1}$$

Earthquake load is taken from the standardization design horizontal and vertical direction floor response spectrum of ACP1000 reactor outer containment and protective plant of horizontal, is an envelope value result of eight kinds of foundation parameter. OBE seismic peak ground acceleration is 0.1g. SSE seismic peak ground acceleration is 0.3g. Frequency is expanded by 15%. Each constraint location chooses corresponding elevation response spectrum. Spectrum Type selects Multiple Points. Modes Combination Type chooses SRSS method.

Finally, according to design conditions and accident conditions, combinational simulation is calculated by using ANSYS Design Assessment.

3. Results and discussion

By CFX flow field calculation, the surface air pressure of VNA system is shown in Table 4, it can be seen from Table 4, since the chimney close to the nuclear island, its surface pressure is more complicated. It is more relative to the basic wind pressure. This situation is that the chimney near the nuclear island, making it flow around occurred change, result in the surface pressure tremendous changes. Therefore, in the structural design of wind-resistant, pressure should be used by the aerodynamic calculation in structures under wind loads analysis. In table 4, V represents the datum velocity, P_+ represents the positive pressure, P_- represents the negative pressure.

Table 4: Extreme value of chimney surface pressure

Conditions	V (m/s)	P_+ (Pa)	P_- (Pa)
Wind Direction 1	68.4	7176.09	-30062.6
	71.4	5126.62	-18945.4
Wind Direction 2	68.4	5951.93	-26072.0
	71.4	4000.76	-16681.2
Wind Direction 3	68.4	6181.69	-24145.5
	71.4	4433.41	-23495.7

In design condition (self-weight + annex-weight + OBE seismic load + a once-in-a-century great wind speed), pipe stress is 46.02MPa, a minimum safety factor 3.03 in the wind direction 3. And horizontal holder and vertical guide bracket have the lowest safety factor in the wind speed direction 2. However, the VNA satisfies the verification criteria. Stress extremum of components are shown in Fig5 (a) to (f), in which that (a) is component of horizontal tube axial stress extreme value, (b) is component of vertical tube axial stress extreme value, (c) is tubule axial stress extreme value, (d) is components of horizontal holder stress extreme value, (e) is vertical guide brackets stress extreme value, (f) is vertical fixed bracket stress extreme value (Fig 4 and Fig 5 to do the same labelling)

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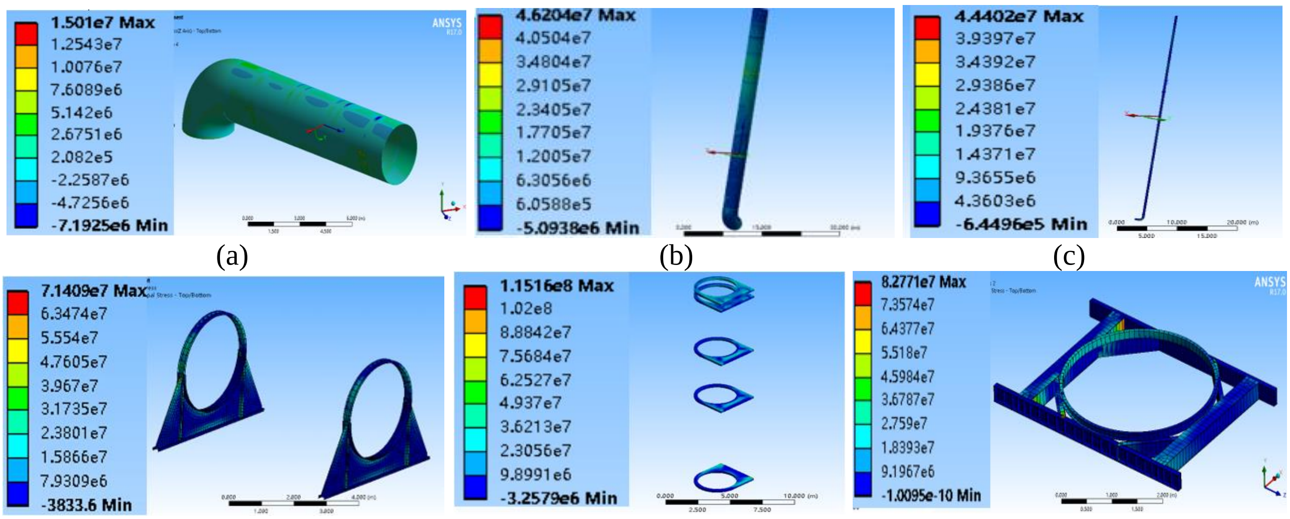

(d) (e) (f)

Figure 3: Stress extremum of components in design condition

In accident condition 1 (self-weight + annex-weight + tornado wind load), VNA FRP chimney horizontal structure safety is lowest when Wind in direction2, the safety coefficient is 6.17. Saddle support of horizontal pipe safety coefficient is greater than 2.07. The position with high stress level is the bracket connection area of the hoop, having adequate safety allowance. The safety factor of the vertical chimney is lowest to 17.03, and ring stress level is lower. So it has a big safety margin. The highest stress level part of the fixed bracket of vertical chimney occurs in the area of contact with the chimney and oblique support, but can guarantee adequate safety allowance. The safety coefficient of guide brackets is greater than 3.75, there is a big safety margin, and meeting the strength requirement. Stress extremum of components in this condition are shown in Fig 4 (a) to (f).

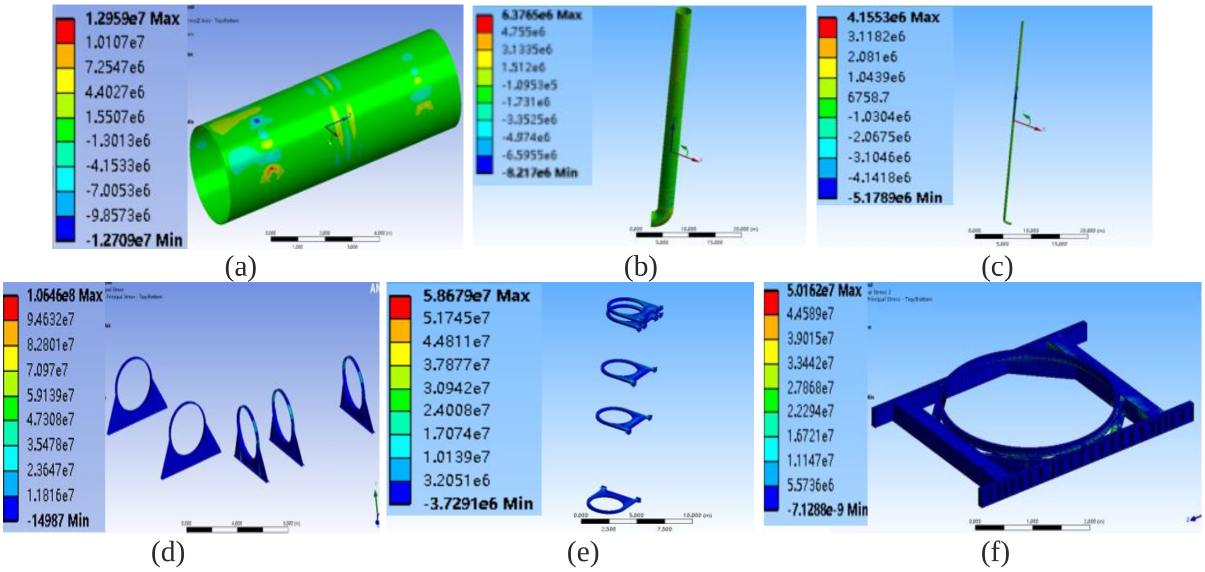

Figure 4: Stress extremum of components in accident condition 1

In accident condition 2 (self-weight + annex-weight + SSE seismic load), Vertical FRP pipe max hoop stress is 89.38 MPa. And its max axial stress is 79.30 MPa. The maximum of film stress + bending stress of steel structures on vertical pipe is 111.10 MPa. Its safety coefficient is 1.98. But due to the structure itself is flexible structure, and its seismic performance is good, the vertical FRP pipe stress level is less than the allowable stress design. Structure under seismic load is safe. Stress extremum of components in this condition are shown in Fig 5 (a) to (f).

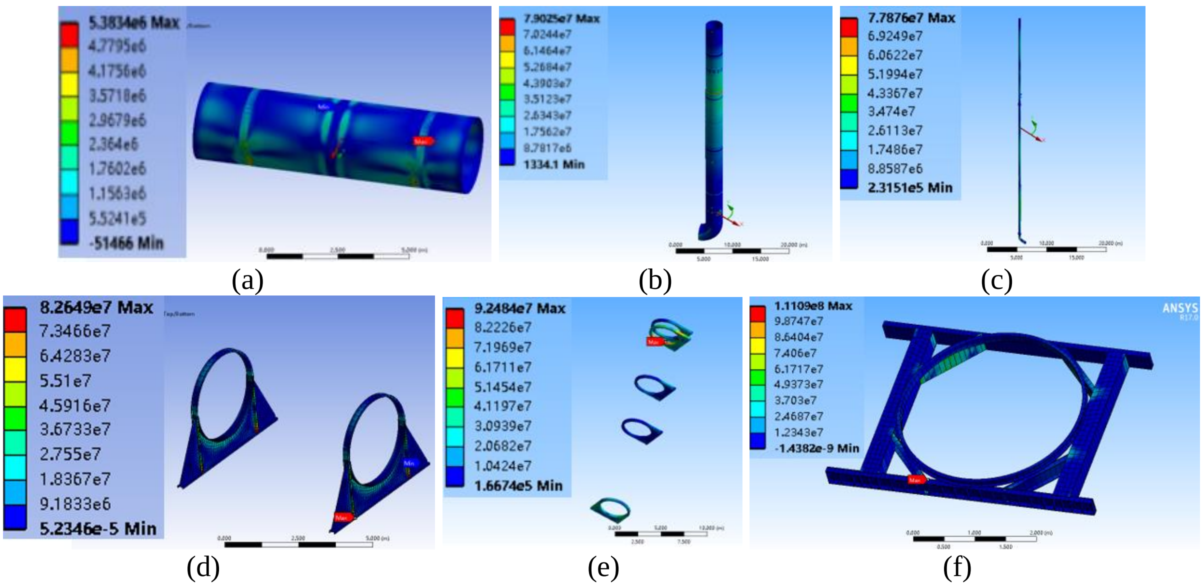

Figure 5: Stress extremum of components in accident condition 2

The stress level of system components under all conditions is shown in Figure 6. In which that σ_{hh} represents horizontal pipe hoop stress extreme value; σ_{ha} represents horizontal pipe axial stress extreme value; σ_{vh} represents vertical pipe hoop stress extreme value; σ_{va} represents vertical pipe axial stress extreme value; σ_{hb} represents horizontal holder stress extreme value; σ_{gb} represents vertical guide brackets stress extreme value; σ_{fb} represents vertical fixed bracket stress extreme value.

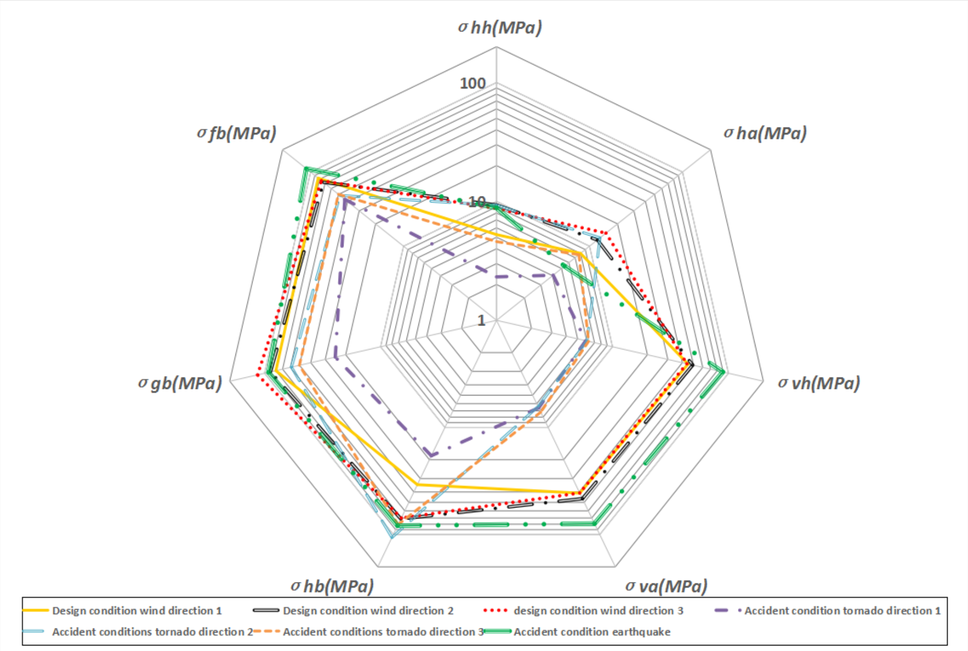

Figure 6. VNA system components stress extreme values

The safety factor summary of system components under all conditions is shown in Figure 7. In which that n_{hp} represents safety factor of horizontal pipe; n_{vp} represents safety factor of vertical pipe; n_{hb} represents safety factor of horizontal holders; n_{gb} represents safety factor of vertical guide brackets; n_{fb} represents safety factor of vertical fixed bracket.

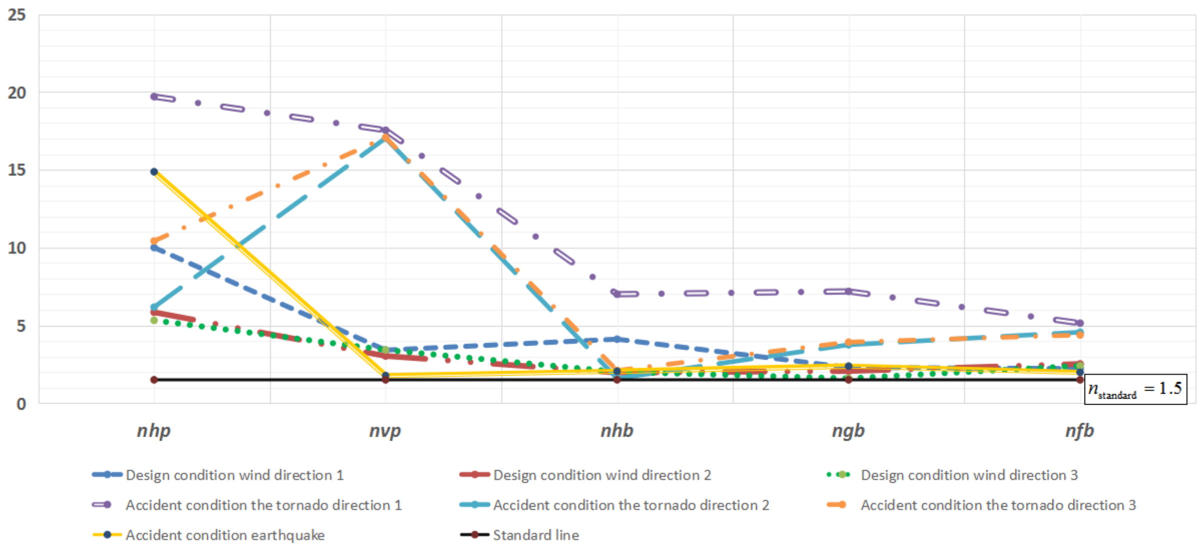

Figure 7: VNA system components safety factor

4. Conclusions

The simulation results show that the stress level is the highest in accident condition 2, which is the control condition of structural analysis, and the stress level of design case and accident condition 1 is lower than that.

The safety factor of horizontal section of the chimney, the vertical section of the chimney, horizontal pipe supports, vertical pipe bearing bracket and vertical pipe guide brackets is all greater than 1, meeting the strength requirements. The maximum stress of the vertical chimney occurs at the point where the highest bracket intersects the chimney. The safety factor of the chimney is more than 1.77, and the hoop stress level is lower, with a certain safety margin. The maximum stress of the fixed bracket of the vertical chimney is in contact with the chimney and its own inclined support, but the safety factor is greater than 1.98. It has a certain safety margin. The maximum stress of the vertical guide support of the chimney is located at the highest support where is in contact with the chimney cylinder. It is recommended to change the steel grade of fixed bracket and guide supports to Q345C, while increasing the thickness of the highest guide frame. The horizontal holders could use the Q235B steel grade.

There are some suggestions that on the one hand the vertical section of the chimney, fixed bracket and guide bracket must be strictly controlled the quality of manufacture and installation, on the other hand, if conditions permitted the data stress should be monitored and accumulated in a period of time. There is need to install the rubber gaskets Especially in the mutual contact area between vertical fixed bracket and FRP pipe and the contact area between guide brackets and FRP pipeline. They could mitigate the extreme value of contact stress. In addition, according to the application environment and load requirements of structure, the material and process should be strictly controlled when equipment is manufactured, to make the FRP structure meeting or exceeding the design parameters.

This paper provides effective technical support and engineering application reference in wind-resistant and seismic design for VNA exhaust chimney of the third-generation nuclear power plant and the general towering buildings.

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