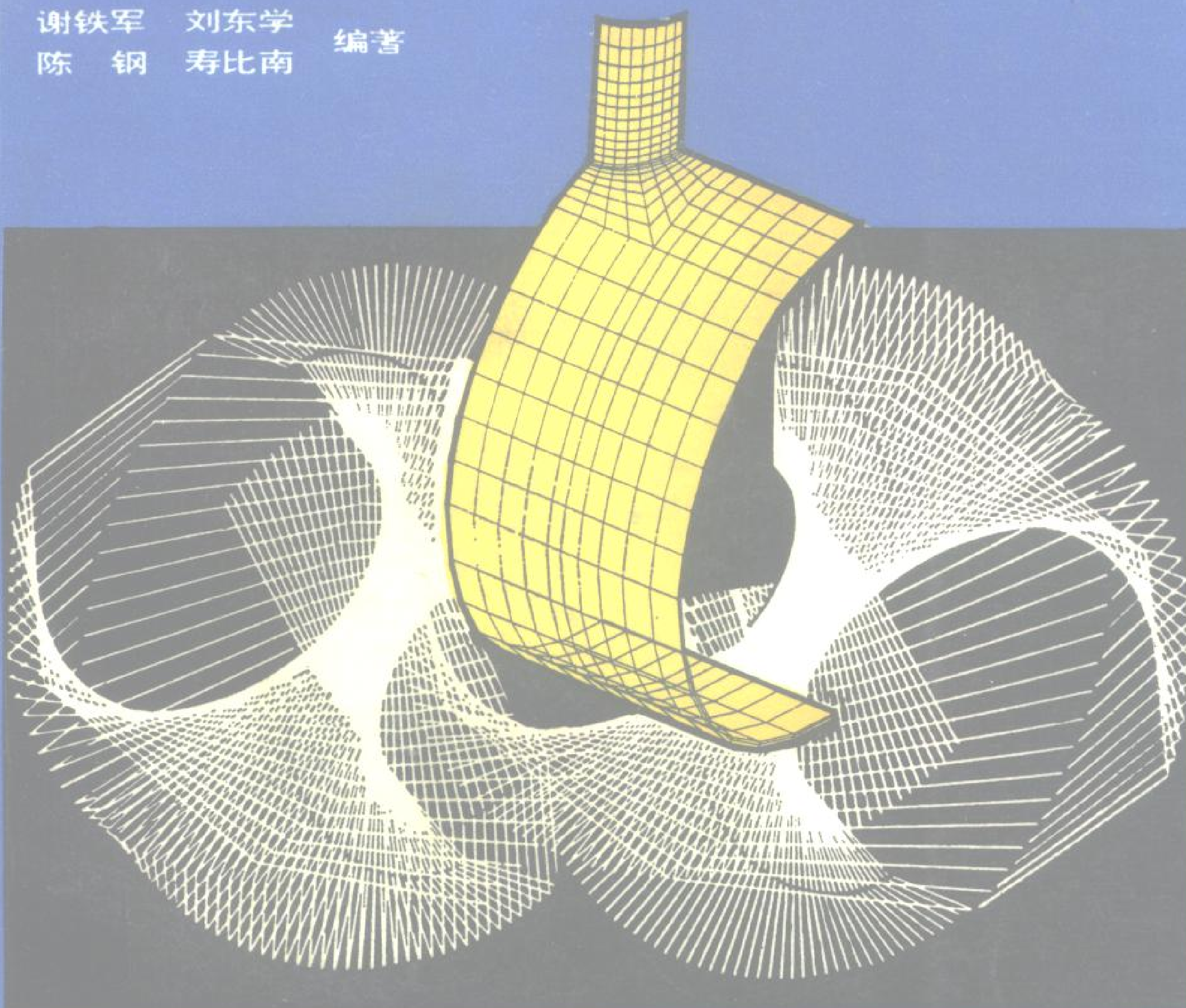
压力容器应力分布图谱

AN ATLAS OF STRESS DISTRIBUTION PATTERNS FOR PRESSURE VESSEL

谢铁军　刘东学
陈　钢　寿比南　编著



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(京)新登字 207 号

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北京科学技术出版社出版
(北京西直门南大街 16 号)
邮政编码:100035

新华书店总店科技发行所发行　各地新华书店经销
北京语言学院出版社印刷厂印刷

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787×1092 毫米　16 开本　23.5 印张　586 千字
1994 年 6 月第一版　1994 年 6 月第一次印刷
印数 1—3000 册

ISBN7-5304-0924-7/Z・426　定价:48.00

内 容 简 介

本书是描述典型压力容器结构及常见缺陷处应力分布的图册。通过大量的有限元计算、弹塑性力学分析及实验应力测试，给出了压力容器基本结构(壳体、封头)、封头与筒体连接、封头上开孔接管(各种补强)、壳体上开孔接管、斜接管、切向接管、典型受压元件(法兰、弯管)、典型容器结构(如加氢反应器、气瓶、管板、蒸压釜等)、常见缺陷(错边、棱角度、凹坑、孔洞等)的直观应力分布图，并给出了一些结构的最大应力集中系数估算公式或曲线。全书包括 9 大类结构，110 多种模型的近 300 幅应力分布图，是一部从事压力容器研究、设计、制造、检验与操作的工程技术人员必备的工具书。

Abstract

This book gives the stress distribution patterns for typical pressure vessel structures and common defects. The patterns presented in this book are based on finite element stress analysis, elastic-plastic mechanics calculation or strain measurement. The clear stress distribution patterns for main components and typical structures of pressure vessel such as shells and heads, connections between heads and cylinderical shells, openings and nozzles (with various reinforcements) in heads or shells, oblique or tangential nozzles in shells, typical pressured parts (flanges, elbows), typical vessel structures (hydrogenation reactor, gas bottles, tubesheets and steam autoclave, etc.) as well as effects of defects commonly encountered such as misalignment, angularity, pits and cavities were included. The estimate formulas and graphs for determining the maximum stress-concentration factors of some structures were also included. A diversity of about 300 stress distribution patterns deduced from more than 110 models of 9 kinds of structural catalogues make the atlas most helpful for those engineers and technicians who engaged in scientific research, design, manufacture, inspection and operation of pressure vessel.

前　　言

强度问题是压力容器研究、设计、制造及检验工作中的一个首要问题，目前，国内外有关容器应力分析方面的研究工作很多，但大多是以理论为主，着重于方法、手段进行的，实例应力分析很少。加之以往计算手段上的限制，容器结构详细的应力分析也难以做到。对于工程技术人员来说，很少用那些复杂的理论去分析一个具体结构的应力，他们更希望不经复杂的计算，就能根据经验直观地看出某种结构大致的应力分布情况。本书就是基于这种想法，对大量的实际容器进行应力计算及测试，为工程技术人员提供大量现成的典型结构应力分布图，即为他们提供一种"经验"，使他们能十分简便地参考这些图例，分析出所处理的结构的应力分布情况，掌握其受力特点和强度状况，抓住问题的关键，合理地进行设计和检验。我们热切地希望本书能成为从事压力容器研究、设计、制造、检验及操作的工程技术人员很好的参考资料，为他们各自的工作提供便利和帮助。

本书的内容主要来源于劳动部 1991 年科研课题"典型压力容器结构及常见缺陷处应力分析及应力图谱研究"(编号:LH－G90－01)，该课题由劳动部锅炉压力容器检测研究中心、全国压力容器标准化技术委员会和大连理工大学化工机械系联合承担完成。本书中的大部分压力容器应力分布图是由编著者通过应力分析做出的，部分来源于有关文献资料的收集整理。应力分析手段主要包括有限元应力分析、电测法及光弹法实验应力分析、弹塑性力学分析等。全书共包括压力容器结构九大类，计 110 种模型的应力分布图约 300 幅。这些图谱量大面广，囊括了压力容器中的大部分典型基本结构、局部结构、受压元件及常见缺陷。目前，我国压力容器设计的另一规程——应力分析设计法即将推行，如此大规模的压力容器结构直观应力分布图册的出版发行，亦将有助于这一设计方法的实施运用。

本书各部分的内容由以下人员编写，第一章:谢铁军;第二、三章:谢铁军、寿比南;第四章:谢铁军;第五章:谢铁军、寿比南;第六章:刘东学;第七章:寿比南、刘东学;第八章:谢铁军、刘东学、寿比南;第九章:陈　钢、谢铁军等。参加本书编写工作的还有刘益荣、熊　华、何处仁、李　勇、陈学东、徐佩珠、沈雪萌、桑瑞鹏、王　冰、曲　杰、李　毅、修长征、杨铁成、魏　安、王桂晶、郭　彤、肖　茜、董晓渝等同志。李学仁、贺匡国、李建国等同志为本书进行了审稿工作，在此对他们的辛勤工作表示感谢。

本书在编写过程中，自始至终得到了王韩挪、李学仁、王东岩、俞宽铣、金恒昀、刘益荣等领导及专家学者的大力支持和帮助，清华大学的陆明万教授对本书的内容进行了仔细的评阅，在此对他们谨致以诚挚的感谢。同时，本书在编写过程中，还得到了劳动部综合计划司、劳动部锅炉压力容器安全监察局、机电部合肥通用机械研究所、清华大学工程力学系等单位有关同志的大力协助，在此一并表示感谢。

使用本书时，请首先仔细阅读书前的"使用说明"，以免发生误解。

由于编著者水平和时间的限制，书中难免有错误和不足之处，恳请读者在阅读参考时予以谅解并不吝赐教，我们将不胜感激。

编　著　者

1994 年 6 月

目　　录

使　用　说　明

1.　结构的选择

本书中所分析的结构主要来源于：

a. 有关压力容器的标准规范(如GB150，ASME，AD等)中所推荐结构。

b. 化工部设备设计技术中心站编制的《化工设备图册》中所列出的推荐结构。

c. 工程图纸及实物容器结构。

d. 有关文献资料。

e. 一种结构的尺寸系列(如开孔接管的不同开孔率)。

f. 对于一个整体容器，一般取其应力集中较大或应力状况较复杂的局部结构进行分析研究，如封头与筒体的连接部分、开孔接管的根部、缺陷附近等。

2.　应力分析方法

2.1　关于理论分析

对于压力容器的基本结构，如壳体、封头等，主要引用有关文献中的板壳理论及弹塑性力学理论的分析结果，这些理论都属经典成熟理论，它们是压力容器结构应力分析的基础。

2.2　关于有限元应力分析

2.2.1　软件情况简介

在本书内容的应力分析中，大量采用了有限元应力分析技术，有限元分析软件主要采用"PV系列压力容器应力分析专用程序"和"SW4压力容器专用有限元分析软件包"。

"PV系列压力容器应力分析专用程序"为劳动部锅炉压力容器检测研究中心与大连理工大学联合开发的专业化、自动化有限元应力分析软件包，是针对压力容器结构而专门设计的。该软件于1990年11月通过劳动部鉴定，1993年6月获劳动部科技进步奖。"PV系列压力容器应力分析专用程序"具有较强的前处理功能，几何、载荷、约束等数据全部自动生成。软件所含有的有限元单元适合于压力容器结构应力分析，结果可靠，能满足工程计算的需要，是一套具有国内先进水平的压力容器有限元分析软件。软件开发成功后，已先后应用于加氢反应器、水夹套、容器法兰、气瓶、接管、封头等的应力分析中，并在国内制造厂取ASME U2资格的设计及国家科委课题"带缺陷压力容器安全性评估研究"中发挥了重要作用。目前，该软件已在本行业内推广应用，解决了许多压力容器应力分析方面的问题。

"SW4压力容器专用有限元分析软件包"为清华大学和全国压力容器标准化技术委员会联合开发的有限元分析程序。该程序由轴对称(包括平面问题)结构有限元程序和"T"型结构有限元程序组成。SW4软件包1991年通过了由国家技术监督局主持的技术鉴定，软件经多年实际工作检验，结果是可靠的。

2.2.2　计算中所选用的单元

应用"PV系列压力容器应力分析专用程序"对结构进行有限元应力分析时，轴对称问题选用轴对称8节点等参元，三维问题选用带内部自由度的三维8节点拟协调元Q_{CS}(一般情况下)和非协调无Q_6(有较大弯曲时)。

应用"SW4压力容器专用有限元分析软件包"进行计算时，轴对称问题采用轴对称三角

元，弯管采用8节点壳单元，厚壁三通全部采用8节点三维单元，薄壁三通沿相贯线采用3～5带8节点三维单元，其它部分采用8节点壳单元。

这些单元都是精度较高的单元，具有较坚实的理论基础和长期使用的实践证明，利用这些单元及它们的组合对压力容器结构进行应力分析，可以保证计算的精度。

2.2.3 网格划分

网格划分、数据准备工作一般用计算机自动生成技术形成，以避免人为产生的错误，并且在计算时还有数据的检查和诊断。为保证计算精度，网格都是经过精心调整的，经过粗细几种网格形式的试算，当其误差较小、且计算结果趋于稳定时，一般取较密集的网格进行计算。应力集中较大或结构形式较复杂处，对网格进行加密处理，以便更好地反映应力集中情况。

2.2.4 计算结果与试验结果的比较

软件在编制、鉴定及使用过程中，与多种结构的理论解（如圆筒、球壳、梁、凹坑等）及电测试验或光弹试验的结果（如封头、接管等）进行了比较，计算结果与解析解或试验结果吻合较好，证明软件有较好的计算精度，其计算能够满足工程需要。这些对比的实例数据是大量的，在此不一一列举。本书中只选择一些工程实际结构与有限元计算结果的比较应力分布图列入到图谱中，以供参照。

2.3 关于试验应力分析

本书应力分析采用的试验方法有两种，即电测试验法和光弹试验法。在这些试验结果中，大部分取自国外有关机构对球柱壳上径向、切向、斜向接管的光弹试验研究工作及对热器管板的电测试验研究工作。另一部分是编著者参与的对实物容器结构的应力电测试验工作（如椭圆形封头中心开孔接管、变径段的应力测试）。对这一部分的一些结构还进行了有限元分析，计算结果与试验结果吻合较好。

3. 应力分布图谱的使用说明

3.1 应用图谱的方式

a. 参考类——应力分布趋势

图谱中的大部分结构的应力分布图是单一的，既没有类似结构的尺寸系列，也没有给出应力集中计算曲线或公式，如加氢反应器、法兰、平封头等，这些图只代表所给尺寸及工况下结构的应力分布，在利用其对同类结构不同尺寸及工况下的模型进行应力分析时，只能参考之，用以定性地分析所处理结构的应力分布趋势，但不能用内插或外延的方法对其应力值的大小进行定量计算。

b. 分析类——应力分布及应力计算

图谱中的某些应力分布图是由相同结构的一系列尺寸模型计算得出的，它不仅有几个系列尺寸下的结构应力分布图，而且还配带有解析解（如基本结构中的壳体、封头等）或者最大应力集中系数估算经验公式或曲线（如柱球壳径向接管、常见缺陷等），利用这些系列化的应力分布图，不仅可以定性地分析出处处理的同类结构的应力分布情况，而且利用这些解析解、经验公式或估算曲线，还可以定量地求出所处理结构的应力值或估算出其最大应力集中，其应用具有更广泛的意义。

3.2 应力分布截面的选取

应力分布图截面的选取按以下原则：对反映整体应力分布情况的（轴对称结构），选沿轴线的纵剖面；对面部结构，一般选有代表性或最危险的截面（如开孔接管、常见缺陷等）。对应力集中部位，一般画到其应力集中基本消失，应力趋于平稳的范围为止。

3.3 使用应力分布图的注意事项

3.3.1 结构基本情况

每一应力分布图的结构基本情况，如结构示意图、尺寸、设计（操作）条件、计算模型（网格）、分析方法、参考文献等信息均包含在应力分布图前的结构基本情况表中。

3.3.2 各种线型所代表的应力

除图中特殊说明外，一般规定：

————————	代表环（周）向应力 σ_θ 或第一主应力 σ_1 或无量纲应力分布曲线 $\sigma_\theta(\sigma_1)/S$（薄膜应力）
－－－－－－－－－	代表经（轴）向应力 σ_φ 或第二主应力 σ_2 或无量纲应力分布曲线 $\sigma_\varphi(\sigma_2)/S$（薄膜应力）
—·—·—·—	代表径向应力 σ_γ 或第三主应力 σ_3 或无量纲应力分布曲线 $\sigma_\gamma(\sigma_3)/S$（薄膜应力）

3.3.3 计量单位

除非图中特殊说明，本书应力分布图中应力曲线上所标注的应力数值，其计量单位均为MPa。而无量纲应力分布曲线上的数值为此处的应力集中系数，即该处应力与薄膜应力的比值。

除非特殊说明，图中所标注的尺寸（长度）计量单位均为mm。

3.3.4 应力基准线（零应力线）

分两种情况：

a. 以容器壁面为基准：结构形状不复杂时，内壁应力以内壁为基准，外壁应力以外壁为基准。

b. 单独外引基准线：当结构形状较复杂时，用容器壁面本身做基准难以清楚表达应力分布情况，采用外引一条基准线。

注意：在应力分布图中，正中（拉）应力前加"＋"号表示（一般省略），负的（压）应力前加"－"号表示。正的或负的应力以基准线为界，分布在基准线的两侧。

3.3.5 应力分布图的几种画法

a. 以容器壁面为基准线，沿容器壁面形状画出应力分布图。典型的如：薄壁壳、封头与筒体连接、弯管、水夹套等。

b. 单独外引基准线，基准线位于容器内外壁两侧，并取沿容器壁面母线的大致走向，在基准线上画出容器壁面相应位置的应力分布图。典型的如：加氢反应器、封头上的开孔接管、柱球壳上的径向切向斜向接管等。

c. 单独外引基准线，不考虑结构形状因素，用相应的位置尺寸一应力值坐标系，以尺寸坐标轴为基准线，按与结构相对应的位置尺寸在坐标系中做出应力分布图。典型的如：凹坑、孔洞等缺陷。

d. 对厚壁结构，有时要表达沿壁厚的应力分布，则取连接并垂直于内外壁的线为基准，沿此线画出其应力分布。典型的如：厚壁圆筒体、厚壁球体等。

Explanation of Usage

1. **Selection of Structures**

The structures analyzed in this atlas were selected from:

a. Recommended structures in the relevant pressure vessel standards, such as GB150 Standard, ASME Pressure Vessel Code, AD Code. etc.

b. Recommended structures in 'Atlas of Chemical Equipment' edited by the Technical Centre of Chemical Equipment Design under the Ministry of Chemical Industry of P. R. C.

c. Structures appeared in engineering drawing or in existing vessels.

d. Relevant literatures.

e. Serial dimensions of the same structural type, such as different opening rate of opening and nozzle connection of an integral vessel.

f. The local details in an integral vessel where a higher stress concentration factor or a rather complicated stress state were expected, such as the connective section between cylindrical shell and head, the root of opening and nozzle connection, the areas adjacent to defects, etc.

2. **Methods for Stress Analysis**

2.1 Theoretical Analysis

For the basic structures of pressure vessel, such as shells, heads, etc., the analysis results in the relevant literatures based on the shell theory and elastic-plastic mechanics theory, which were the classical and well-established theories as well as the basis of stress analysis for pressure vessel, were cited in this atlas.

2.2 Finite-element Stress Analysis

2.2.1 Brief Introduction of Softwares

Finite-element analysis is widely used in stress analysis of pressure vessel structures in this atlas. The main softwares used are 'PV Serial Special-purpose Stress Analysis Program for Pressure Vessels' and 'SW4 Special-purpose Finite-element Analysis Software Pack for Pressure Vessels'.

The software 'PV Serial Special-purpose Stress Analysis Program for Pressure Vessel' was jointly developed by the Center of Boiler and Pressure Vessel Inspection and Research (CBPVI) of the Ministry of Labor of P. R. C. and Da Lian University of Technology (DUT). It is a specialized and automatic finite-element stress analysis software pack directly aimed at various structures of pressure vessels. The software had passed technical appraisal organized by the Ministry of Labor in Nov. 1990 and won a science-technology progress award of the Ministry of Labor of P. R. C. in Jun. 1993. This software possesses good pre-processing ability. All data of geometrical parameters, applied loads and restraint conditions of the structure to be analyzed can be automatically generated. The elements involved in the software are suitable for stress analysis of pressure vessel structure and the calculative results delivered are reliable and satisfactory for engineering purpose. It is an advanced finite-element stress analysis software of pressure vessel in China, and has been used in stress analysis of hydrogenation reactor, water jacket, flange of vessel, gas bottle, nozzle, head, etc. It did play an important role both in the design of U2 vessels in some pressure vessel manufacturers to be qulified for ASME certificate and in the accomplishment of the key research project, 'Safety evaluation of Defective Vessels', of the State Science and Technology Commission of P. R. C. The software has been populizing in the relevant field successfully.

'SW4 Special-purpose Finite-Element Analysis Software Pack for Pressure Vessel' is jointly developed by Tsinghua University and China National Standards Committee of Pressure Vessel. The software pack consists of finite-element analysis programs both for axisymmetrical structure (including plane-problem) and for tee structures. SW4 software had passed technical appraisal organized by China National State Technical Supervision Bureau in 1991. SW4 software pack can provide reliable calculation results as proved through several year's application.

2.2.2 Elements Seleted for Calculation

Axisymmetric eight-node isoparametric element were selected for calculation of the symmetric problems, and a three-dimensional eight-node conforming element Q_{C5} (for general cases) or a non-conforming element with internal degree of freedom Q_6 (for rather large bending cases) were adopted for calculation of three-deminsion problems in the PV serial software.

As for the SW4 software pack, a symmetric triangle element was used for calculating symmetric problems, eight-node shell element for elbows, eight-node three-dimensional element for thick-walled tee, 3～5 bands of eight-node three-dimensional element for the intersection line of thin-walled tee and a eight-node shell element for other parts of thin-walled tee.

The elements used are of high accuracy. All of them are based on a sound theoretical basis and are dependable through a long-period application. Thus, a precise calculation can be expected so long as the stress analysis is based on them or on the combination of them.

2.2.3 Mesh-division

Mesh-division and data preparation for stress analysis are automatically generated by auto-generation program of computer; further more, an automatical check-and-diagnosis function during calculation are also provided. Therefore, artificial error can be eliminated. In order to assure the accuracy of calculation, mesh-division were carefully regulated through comparision of the trial calculative results of different mesh sizes. Generally, a finer mesh was selected while a stable trial calculative results and an accepted error were reached. Sometimes, a refinement mesh should be conducted at the regions of high stress-concentration or of complicated structure in order to identify the details of stress concentration.

2.2.4 Comparing the Calculative Values with Experimental Values

During compilation, appraisal and application of the software, the calculated results were compared with the theoretical solution of all sorts of structural types (such as cylinder, spherical shell, beam, concave pit, etc.) and with the measured stress values delivered by strain-gage method or photo-elastic method (such as nozzles, heads, etc.). A good coincidence of comparison had been obtained. That is to say, the softwares used have good calculative accuracy, they are satisfactory for the needs of engineering calculation.

Although, it is impossible to list all of the numerous experimental data here, some selected comparing stress-distribution curves of engineering structures together with the calculative results delivered from finite-element analysis were presented in this atlas for reference.

2. 3 Experimental Stress Analysis

Two kinds of experimental stress analysis methods were adopted in this atlas, i. e. strain-gage method and photo-elastic method. Most of the experimental results in this atlas were collected from the research results of relative foreign orgnizations, such as the photo-elastictest results of radical, tangent or oblique nozzles of cylinder, and the strain-gage test results of tube-plate of heat exchanger; the others were the test results completed by the authors of this atlas, such as the test results of centre-opening nozzles in elliptical head and of transition section, etc. Good correspondance between test results and finite-element stress anlysis calculation had achieved in the latter circumstance.

3. How to Use the Stress Distribution Atlas

3. 1 Modes of Application

a. Reference mode: trend of stress destribution

The stress distribution graphs of most structures are single in this atlas, neither serial dimensions of similar structure nor formula or curves for calculating stress concentration were provided, such as hydrogeneration reactor, flange, flat head, etc. Graphs of this mode only give stress distrubition pattern of the structure under assigned dimensions and limited working parameters. For the sake of analyzing the stress distribution of some structures of the same type but with different dimensions and/or working parameters, only a qualitative trend of stress destribution pattern can be achieved. Be sure, one cannot get a quantitative stress destribution pattern from these graphs even through interpolation or extrapolation method being adopted.

b. Analysis mode: stress destribution and stress calculation

Some stress distribution graphs were calculated based on a serial dimensions of model with same structural type. Not only stress distribution of structures with serial dimensions are available, but also the analytic solution (such as shell, head, etc. of basic structure) or empiric formula/curves for estimating the maximum stress concentration factors (such as radical nozzle in cylinder, common defects, etc.) were provided. Thus a qualitative stress distribution and a quantitative stress value or a quantitative estimated maximum stress concentration factor of the same category vessel can be obtained by using the serial stress distribution graphs and the analytic solution, empiric formula or estimated curves provided. Therefore, this kind of analysis mode is more useful.

3. 2 Selection of Stress Distribution Section

Principals for selecting stress distribution section are as follows:

For general stress distribution pattern of axisymmetrical structures: longitudinal section along the axis of the structure;

For stress distribution pattern of local structures: the representative section or the most dangerious section, such as opening and nozzle connections, common defect areas, etc.

For stress concentration regions: generally, the boundry of stress distribution graph were limited to a region where the effect of stress concentration had vinished and stress distribution had tended towards smooth on the whole.

3. 3 Points for Attention in Using Stress Distribution Graphs

3. 3. 1 Basic Situation of Structure

Information of basic situation of structure concerned with the corresponding stress distribution graph, such as sketch of structure, dimensions, design/operation conditions, model(mesh) used in calculation, analyzing method, bibliography, etc. are listed in a table directly ahead of the stress distribution graph.

3. 3. 2 Legend

Unless otherwise mentioned, the legend for different styles of line appeared on the stress distribution graphs indicate:

————————	circumferential (grith) stress σ_θ or first pricipal stress σ_1, or non-dimensional stress distribution curves $\sigma_\theta(\sigma_1)/S$(membrane stress)
— — — — — — — —	longitudinal (axis) stress σ_φ or second principal stress σ_2, or non-dimensional stress distribution curves $\sigma_\varphi(\sigma_2)/S$(membrane stress)
——·——·——	radical stress σ_r or third principal stress σ_3, or non-dimensional stress distribution curves $\sigma_r(\sigma_3)/S$(membrane stress)

3. 3. 3 Unit of Measurement

Unless otherwise mentioned, the unit of stress value appeared on stress distribution graph is MPa. The values shown in non-dimensional stress distribution graphs are the stress concentration factor at the site, i. e. the ratio of the actual stress to the membrane stress at the site.

Dimensions shown in the graphs are given in mm, only if otherwise stipulated.

3. 3. 4 Datum of Stress (nil-stress curve)

a. While the contour of vessel is simple, the internal surface of vessel is taken for the internal wall-stress datum of the vessel; similarly, the external surface is the datum of external wall-stress of the vessel.

b. When the datum coincided with the wall surface of a complicated vessel cannot indicate stress distribution of the vessel clearly, an additional datum shoud be imposed.

Note: In stress distribution graph, put a '+' mark ahead of a stress value to indicate a possitive (tensile) stress (generally it can be ommitted), a '—' mark to indicate a negative stress. Datum is the boundry of possitive and negative stresss, which are located at the each side of it.

3. 3. 5 Some Methods for Drawning Stress Distribution Graphs

a. Taken wall surface of vessel as datum, the stress distribution curves were drawn along with the outline of the vessel. Typical examples are thin-walled shell, connected region between cylinder and head, elbow, water jacket, etc.

b. If an addtitional datum was used, put the datum at the each side of internal-external wall of the vessel with a trend towards the rough sketch of the vessel, stress distribution graph then could be drawn on the datum corresponing to the location of wall surface of the vessel. Typical examples are hydrogenation reactor, opening and nozzle connection in head, radical or tangent or oblique nozzle connection on cylinder, etc.

c. Additional datum was adopted without considering the structure or contour of the vessel. Stress distribution graph was drawn on a dimension-stress coordinate taken the dimension axis as datum. The stress distribution graph on coordinate should be corresponing the locating relationship with the vessel. Typical examples are concaved pits, holes, etc.

d. Thick-walled Structures

In order to express stress distribution normal to the wall surface of a vessel, a interconnect line normal to the internal and external surface of vessel was taken as datum. Stress distribution curve was drawn along the datum. Thick-walled cylinders, thick-walled spherical shells, etc. are the typical examples.