

中国文化遗产研究院

中央级公益性科研院所基本科研业务费专项成果丛书·2013年

文物保护工程与规划专辑 II

——技术与工程实例

中国文化遗产研究院 编

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序

刘曙光

《国家中长期科学和技术发展规划纲要》(2006~2020年)提出,加大对中央级公益性事业单位的支持力度,建立稳定的支持机制。财政部为此专设了中央级公益性科研院所基本科研业务费专项资金(以下简称“基本科研业务费专项”),重点支持40岁以下中青年科研人员开展储备性、创新性、孵化性科研工作。这是国家重视和支持科学与技术工作的一项重大决策。作为以文物保护应用科学研究为主业的科研机构,中国文化遗产研究院是这项政策的受益者。

长期以来,我院一直致力于通过组织、实施重要(大)科研项目,发掘、研究文物保护领域传统技术科学化工作,以解决文物保护与发展过程中遇到的实际问题。但由于经费短缺,在较长时间内制约了我院科研工作的进展。在财政部和国家文物局的关心下,自2007年起,我院开始持续获得基本科研业务费专项资金支持,可以根据重点工作和主要研究方向自主设置课题。

自2007至2013年,我院总计获得基本科研业务费专项资金2654.5万元,先后设立了93个科研课题。这些课题涉及文物保护科技、文物保护工程与规划、社会科学等诸多方面,内容广泛。概括起来,基本科研业务费专项资金的使用,对我院基础建设和科学发展所起到的推动作用,主要涵盖以下四个方面:

一是促进我院逐步确立了“实际需求导向、重点领域突破”的科研基本原则,以及“以项目产生课题,以课题带动研究,结合文物工作和文物保护的实际需求开展科研工作”的科研模式,逐渐强化应用型科研成果对文物保护工程项目的支撑作用,提高工程项目的科技含量,强化软科学成果对文物保护管理决策科学化的支持力度。

二是产生了一批具有较高质量并实现其价值的科研成果,在重要的文物保护工程中较好发挥了技术支撑与引领作用。例如,我院通过基本科研业务费专项先后立项6个课题,投入220万元,支持广西南明花山岩画抢救性修复保护工程项目中渗水病害探测、颜料病害、保护材料与工艺、保护修复技术与方法、环境监测等方向的深入研究,确保了该工程项目的顺利实施,对全国相似石窟、古建筑等文物修复也起到了重要借鉴和示范作用。其他诸如高句丽墓葬壁画原址保护、哈尼梯田申报世界遗产项目、大运河保护规划编制及申报世界遗产项目、应县木塔稳定性监测与研究、援助柬埔寨吴哥古迹茶胶寺工程、海洋出水文物保护、大遗址保护行动跟踪研究等一批重点工作,都借助此项资金的支持而得以顺利开展并取得重要成果,在相关领域发挥了实质性的技术

支撑与导向作用。

三是通过承担基本科研业务费课题，我院锻炼和培养了一批业务强、学风好的青年科研带头人与科研骨干，初步打造了世界遗产研究、考古遗址公园规划、海洋出水文物保护等跨学科、专业化的创新团队，为提高我院的人才队伍素质、促进年轻一代科研工作者成长，奠定了重要基础。

四是通过基本科研业务费课题的开展，为我院科研合作机制和评价体系向着“职责明确、评价科学、开放有序、管理规范”的现代科研院所发展提供了契机。

然而，毋庸讳言，对于我院这样专业领域较为宽泛的科研单位来说，选择适宜的经费投入结构与相对优先次序，仍是需要坚持探索的问题。我们认识到，在基本科研业务费专项的管理使用过程中，单位发展方向、重点科研项目设置和个人研究兴趣的结合，还存在着一个必要的磨合期。要使科研工作者个人的兴趣服从于事业发展大局的需要，在立项以及后期各个阶段，都需要精密的科学筹划和指导管理。

此外，由于课题承担者专业背景差异较大，长期困扰我院的工程项目与科研项目“两层皮”现象，在自主科研业务费专项上亦有表现。如何更好地发挥基本科研业务费专项资金储备性、创新性、孵化性功能，抓好重大科研问题的凝练与确定发展远景和路径，既考虑科研自身规律（科学性、探索性和不确定性），又照应科研成果在工程项目的实践性和可操作性，促进应用技术研发和文物保护工程实际相结合，仍是需要我们今后积极探索和科学实践的重要任务。

本专辑汇集了2007至2011年度我院已结题的基本科研业务费专项成果，既是对以往工作的总结汇报，也借以表达我们不断改进工作现状、提高工作水平的决心。“言之无文，行而不远”，将一个较大的课题内容在有限的篇幅内清晰展显，在一定程度上体现着研究者的提炼与概括能力，同时亦是一次提高与自我修正的学术历练。我们衷心感谢财政部、国家文物局的关心和支持，也由衷地希望及时得到同行的指正与批评。

2013年7月29日

PREFACE

Liu Shuguang

In the *National Guideline on Medium-and Long-Term Program for Science and Technology Development (2006 ~2020)*, the state has promised to enhance the support for central public research institutions with stable mechanisms. Consequently, the Ministry of Finance has created the Central Public Research Institution Basal Research Fund (hereafter the Fund), which sponsors young scholars below 40 to carry out-research projects that have potential, innovative and incubative natures. It reflects the state's strategic commitment to the development of science and technology. As an institution oriented towards applied studies of cultural heritage conservation and utilization, the Chinese Academy of Cultural Heritage (CACH) is a beneficiary of the policy.

CACH has long been dedicated to solving practical problems emerging in cultural heritage conservation and development, by organizing and undertaking significant scientific research projects, and by exploring approaches to the scientific ation of traditional relics' conservation techniques. However, these programs used to be constrained due to lack of funding. With the support of the Ministry of Finance and the State Administration of Cultural Heritage, the Fund has been annually allocated since 2007 to CACH to organize major research projects according to our own key work schedules.

From 2007 to 2013, CACH has received the Fund totaling RMB 26,545,000 *yuan*, with which 93 research projects have been granted. The projects range from cultural heritage conservation technologies, conservation engineering and planning, to social sciences research. With the funds, CACH's institutional constitution and scientific development are largely fostered in four major aspects:

First, our philosophy in research have been further reinforced, which should be demand-oriented and key-focused. As a strategy, research subjects should be derived from practical works, from which academic explorations should be grounded, so that all researches could be closely associated with cultural heritage conservation practices. It is in this way that we try to maximize the application of our research in cultural conservation projects, and upgrade the quality of the latter. Meanwhile, our social sciences researches also have strived for supporting and contributing to the state's cultural conservation policy-making.

Second, a number of research projects have made substantial progress and found advanced application in real conservation works. An exemplar is a series of six projects for the Rock Painting of the Mountain *Huashan* in Ningming, Guangxi. The series, with a total funding of RMB 2,200,000 *yuan*, explores a variety of aspects for salvage rescue and restoration of the rock painting, including examination of water-seepage and pigment diseases, conservation materials and techniques, restoration techniques and methods, and environment monitoring. The series of research is not only contributory to the restoration in practice, but also serves as an instructive model for other restoration projects of China's rock grottos or ancient buildings. Similarly, the Fund have benefited many other substantial projects, such as the protection of Koguryo Tomb's mural

paintings in situ, World Heritage nomination for the Hani Terrace, Conservation Plan and World Heritage nomination for the Grand Canal, the monitoring and analysis on the stability of Ying County's Wooden Pagoda, the international project at Cambodia's Takeo Pagoda, the conservation of underwater heritage, the retrospective and longitudinal study of Large-scale Archaeological Sites, etc. These projects have made remarkable academic advancement and identified future potentials for researches in relevant fields.

Third, with the projects supported by the Fund, many young scholars in CACH have strengthened their academic capability and become more dedicated to heritage conservation. In addition, interdisciplinary research teams have been forged in such key fields as World Heritage studies, archaeological heritage park planning, and restoration of underwater cultural heritage. The teams, imbued with creativeness, are the basis of CACH's future in the academia.

Fourth, through management of the Fund CACH has been able to better streamline the quality control mechanism for research projects management in terms of team organizing and performance assessment, in an aim to develop into a more modernized research institute that is responsible, accountable, open and disciplined.

For CACH, an institution involved in relatively broad and multi-disciplinary fields, it is a difficult task to explore a proper balance in allocating a large sum of fund and giving an effective order of priority. We are fully aware of the long way yet to journey for gearing up to establish an integrate relationship between CACH's long-term goals, the research projects' objectives, and individual's academic interests. In order to better coordinate and guide individual work towards key goals of CACH, more sophisticated organization and management-mechanism is necessary at every phase of the research projects.

In addition, the variety of researchers' backgrounds tends to result in disconnection between practical-based works and academic-oriented projects, an old obsession in CACH which has also been not avoidable in the Fund projects. We will keep working hard to explore practical approaches to further integrate academic research of uncertain and unpredictable nature with real works of definite and pragmatic nature, to identify key research projects with strategic visions, and to make full use of the Fund in supporting potential, innovative and incubative research.

Herewith, we present volumes of reports from the funded research projects between 2007 and 2011. The publication is not only a summary of previous attainments, but also a proof of our determination to improve and advance our work performance. A Chinese saying tells us the importance of writing in itself: Non-elegant words will not become popular. It indeed takes great capability to present a grand project in a paper of limited length, a rewarding training process for our scholars. Hereby, we are especially grateful to the Ministry of Finance and the State Administration of Cultural Heritage for their solicitudes and supports. Last but not least, colleagues' comments and critiques are heartedly welcome and appreciated.

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古建筑木构件横纹承压增强加固技术研究

中国文化遗产研究院文物保护工程与规划所 王林安

摘要: 本文结合木材的微观构造,探讨了木材横纹承压的受力机理和强度设计值的计算方法,得到了应县木塔木构件横纹局压的抗力作用效应比。针对木材横纹局压的受力特点和加固目标,本文提出“插筋法”增强古建筑木构件的横纹局压承载力的技术,研究增强机理和加固后的力学性能,探讨制作工艺及在应县木塔中的应用问题。普柏枋的截面高度相对较小,横纹局压高应力区贯穿整个构件截面,采取棒材两端直接承压的技术;梁枋的截面高度较大,增强棒材一端承压,另一端没有直接承压面,靠棒材与木材之间的胶层摩擦传递荷载。

普柏枋中增强棒材的受力形式相当于木材侧向弹性约束下的轴压问题,因而,先从理论角度分析了侧向弹性约束下棒材的计算长度系数的计算方法,进而求得其长细比和稳定承载力。然后设计了一系列试验验证了理论分析的正确性。同时还研究了木材边距、间距和端距对棒材稳定承载力的影响,计算求得木材边、端距的最小值。最后,通过钢筋增强木材横纹局压标准试件的试验,研究了增强构件横纹局压承载能力随棒材含量增加的变化规律,以及增强构件的破坏形式。在上述研究成果的基础上,本文提出了普柏枋横纹局压增强加固承载力的计算公式。

关键词: 木材横纹承压 增强加固技术试验研究 应县木塔保护

A Study on the Reinforcement Technology for Timbers' Compression Perpendicular Grains in Ancient Buildings

Wang Lin'an

Abstract: Based on the timbers' microstructure, this paper explores the stress mechanism of the wood's compression perpendicular grains and designed strength. The ratio of resistance to load effect is also obtained from Yingxian County Wooden Pagoda. It brings forward the technology that GFRP sticks and steel bars reinforce the timber members whose compression perpendicular grains have excess load and discusses the craftwork in reinforcing the timber members in the Pagoda. The categories of timber members are based on the states of stress of compression perpendicular grains and section size. There are two types of timber members:

The beams on the column head are named Pubai Fang. The beams under the column are named Liang Fu. Pubai Fang has small section size, and partial compression perpendicular grains and high stress area run through the whole member's section. So the whole section should be reinforced, namely two ends of the bars bearing the pressure force. Liang Fu only needs partially reinforced, namely the one end of the bar bearing the pressure, the other end is hanging which depends on the friction between the bar and the timber to transfer the load.

Pubai Fang uses the axial compression of the bar under the timber side to enhance the loading capacity. Under the wood's side supporting, the stable bearing capability of the bars is analyzed theoretically, subsequently a series of tests are conducted. The effect which marginal distance and end distance affect the stable loading capacity and its critical value are studied. An experiment on 12 standard reinforced steel bars is conducted. Liang Fang bears load through the shearing resistance that comes from the effect between timbers and bars. In this paper a series of experiments on shearing resistance in glue line are performed. The variable rule that different thickness and depth glue line affect the load is studied. Subsequently, the critical depth of the glue line is created. The test proves that the technology to reinforce Liang Fang's compression loading capacity perpendicular grains is feasible.

Keywords: compression perpendicular grains of wood, test of reinforcement technology, the preservation of Yingxian Wooden Pagoda.

1 绪论

1.1 课题背景

应县木塔建于1056年,在山西应县县城内,其主要结构构件及构造做法基本上保留了原建时期的面貌,是研究我国早期古代建筑技术及大木制度的重要实物遗存。木塔主体原木结构的高度达52米,目前在世界上还是孤例,成功抵御950余年的风雨侵蚀、地震及战争破坏仍然屹立不倒,具有极高的科学价值和成就。然而,由于年久失修,再加上不当修缮和炮弹袭击以及后来多次地震的损伤累积,当前,应县木塔结构残损严重,尤其是底部三层结构病害缠身,横纹承压构件严重破坏,亟须修缮加固。

应县木塔结构外观五层实为九层,其中有四个结构层为平坐层,也称为“暗层”,夹在各明层之间,是一个中空的双层八边形环状结构。在平坐层内柱子之间和内、外角柱之间架设不同方向的斜撑,形成桁架结构(TRUSS),有如一层刚性加强层,有效地增强了木塔整体结构的强度。中空的部分增加了明层的净空高度,以便安置较高大佛像。其余五层为明层,每层都供奉佛像,除首层供奉的释迦牟尼金身坐像高达11米外,其上四层佛像尺度相对较小。全塔共使用400余攒不同类型的斗拱,平面则采取内、外两圈八边形立柱,内圈主柱8根,外圈主柱24根,形成内外双层柱框层相套的平面结构。

应县木塔结构构件数量众多,为中国现存古建筑木结构之最。主要构件包括柱子658根(主柱312根,直径560~640mm;辅柱346根),阑额及普柏枋共有304根,梁袱248楹(截面尺寸为460mm×430mm),铺作层枋子4800个(截面尺寸约为255mm×170mm),栌斗424个,散斗大约9000个,上述结构构件数量合计约15434件(根),体积达2200立方米,木材重约1300

多吨。

应县木塔结构构件的受力性质主要包括轴压构件（柱子）和横纹承压构件（梁枋）。由于应县木塔的体量高大，自重荷载重，对于底部几层结构而言，由于承载能力不足，大部分横纹承压都出现大的横纹压缩变形和破坏状态，危及应县木塔整体结构的安全，需要进行修缮加固。

本课题重点解决应县木塔原构件及新换构件横纹承载能力的增强加固技术，其目的是对于原木结构构件，在尽可能少的干预情况下，通过增加锚固钢筋（或 GFRP 筋）的方式，将应县木塔底部三层原有结构构件和新换结构构件的横纹承压能力提高到实际荷载工况所需要的水平。主要工作内容是通过试验分析与计算机数值模拟提出增强加固后构件横纹承载能力的计算公式。

应县木塔为山西应县佛宫寺释迦塔的通称，建于辽清宁二年（1056 年）高 67.31m，木塔立面见图 1，剖面图见图 2。



图 1 应县木塔

应县木塔平面为正八角形，用两层柱圈构成外槽。里圈转角处各设 1 根内槽柱；外圈在转角处设 3 根外檐柱，各用 1 根乳枋（联系梁）与内槽柱联结，外檐柱之间和内槽柱之间上端用普柏枋及阑额下部用地枋构成八角形的筒体，见图 3，普柏枋之上是组成整体的斗拱结构层（简称斗拱层）。筒体中央的内槽为使用空间的主体，外槽用作人流通道。

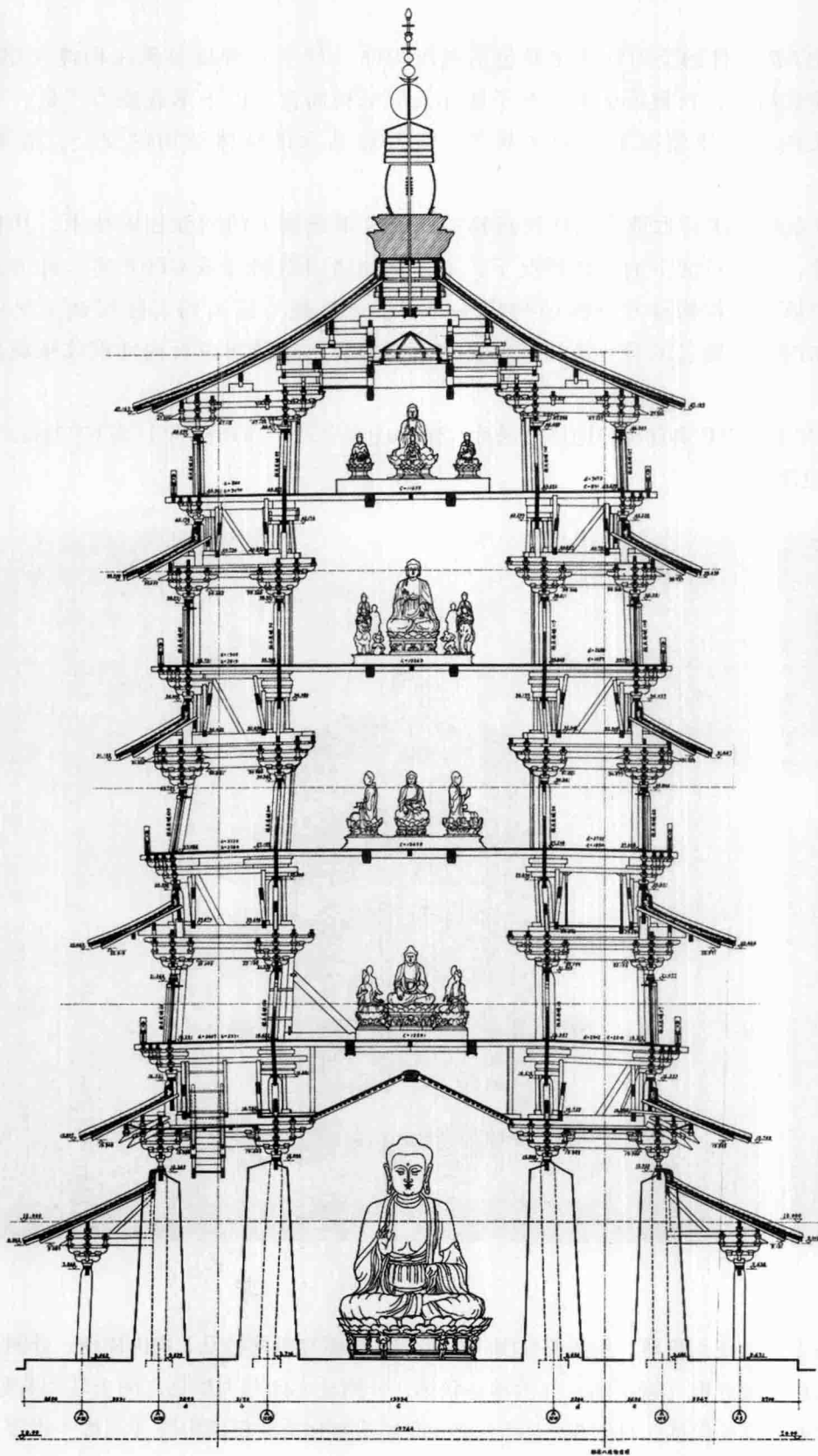


图2 应县木塔剖面

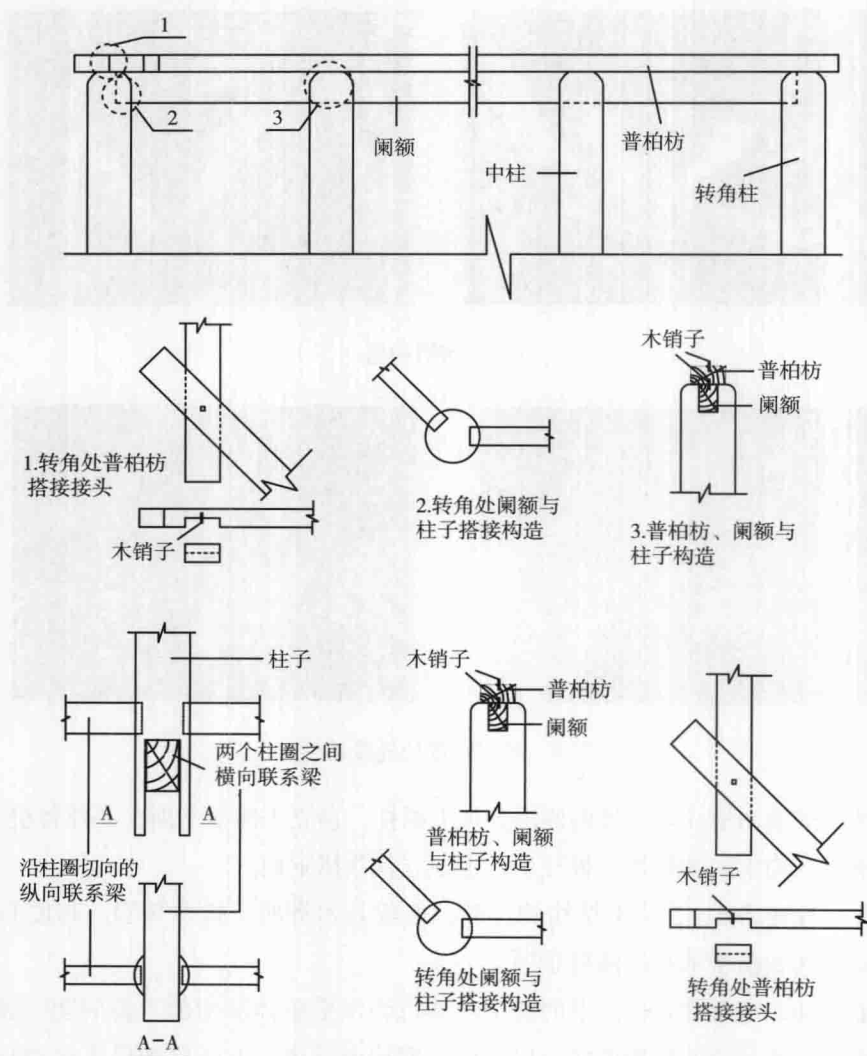


图3 柱框层结构简图

内槽共5层，称为明层。从第2层开始，每一层都支承在沿外槽构筑的暗层（称为平坐）上，图4~6示出暗层的结构特征及构造。因此木塔实质上是9层结构。



图4 四层暗层内部结构

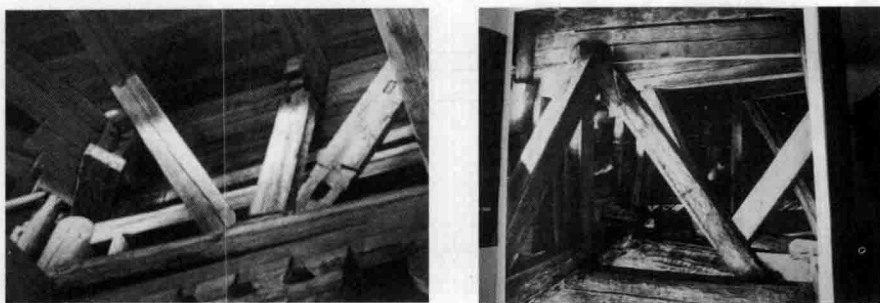


图5 暗层构造

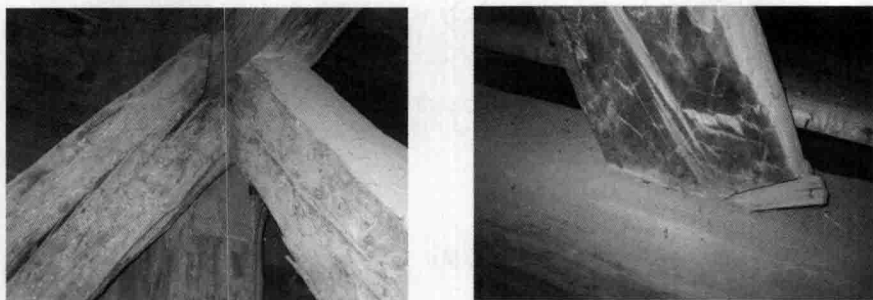


图6 暗层斜撑的连接构造

第1层内槽柱及暗层内槽柱内、外两侧均补加1根柱，顶立于斗拱下面，其他各层（第5层除外）所有外檐柱及内槽柱，均于内侧补加1根柱子，也顶立其斗拱下面。

应当指出唐代只有建造2~3层木结构的经验，而应县木塔明、暗共9层。高度和自重皆成倍增加，使古建筑木结构遇到前所未有的两项难题。

其一是因高度增加，地震荷载作用下的安全可靠成为木塔整体结构的主要问题。建造木塔的辽代匠师参照唐代殿堂内、外分槽的结构形式，用两层柱圈构成筒体，并逐层加设了层高较低称为平坐的刚度加强层。两圈所有柱子都由下至上向内倾斜，称为侧脚，见表1，对筒体形成环箍力。使这一高层木结构孤例的结构体系，在一定程度上类同现代高层建筑，经受多次7~8级地震而依然屹立。

其二是因自重增加，使承受上层柱轴向荷载的梁（普柏枋和乳栿）端横纹承压应力成倍地超过设计强度而产生严重的压缩变形甚至劈裂，见图7~9，导致木塔整体竖向变位。



(a) 普柏枋南面端头残损现状

(b) 普柏枋南面端头残损现状

图7 一层内槽正东面南柱柱头横纹承压构件的残损现状