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# 预制装配式结构梁柱节点被动耗能减振技术 研究现状及展望\*

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**摘要:** 由于预制装配式建筑在高烈度地震区的抗震性能较差, 限制了其推广使用。预制装配式框架结构作为一种常用的抗震体系, 核心部位梁柱节点的连接是影响其抗震性能的主要因素。被动耗能减振技术作为一种成熟的结构振动控制技术应用于预制装配式结构中, 可以显著提高结构的抗震性能。将耗能器放置于梁柱节点外部或者内部, 既与节点形成新的整体部件, 又实现自身被动耗能减振, 形成“承载-耗能”双功能的新型节点。总结了目前常用的被动耗能减振技术中已经成熟的摩擦阻尼器和金属阻尼器复合形成的预制装配式结构梁柱节点, 梳理了本课题组首次提出的预制梁柱耗能铰节点后的研究发展现状以及局限, 提出了一种预制装配式结构梁柱摩擦-金属屈服两级耗能节点, 形成了高性能预制装配建筑结构抗震体系, 对提高我国装配式结构设计和推广装配式结构的实际工程应用, 具有重要的参考意义。结合作者在该领域的研究工作和成果, 给出了该领域的研究方向和未来的发展趋势。

**关键词:** 预制装配式; 梁柱节点; 摩擦阻尼器; 金属阻尼器; 两级耗能

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## State-of-the-art and Prospect of Prefabricated Beam-column Connection with Passive Energy Dissipation Technology

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**Abstract:** Due to the poor seismic performance of prefabricated structures in high seismic regions, its popularization and application are limited. Precast concrete frame structure is a commonly used seismic system, and the beam-column connection is the crucial factor affecting its seismic performance. Passive energy dissipation technology, as advanced structural vibration control technology, can significantly improve the seismic performance of prefabricated structures. The passive energy dissipated device is placed outside or inside the beam-column joint, which not only forms a new integral part with

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the joint, but also realizes passive energy dissipation, thus forming a new type of dual-functional connection with load-bearing and energy-dissipation under seismic loading. The prefabricated beam-column connections with frictional dampers or metallic dampers, and the energy dissipation hinges used in the beam-column connection are summarized. A prefabricated two stage energy-dissipated beam-column connection combined rotational friction damper and flexural yielding metallic damper is put forward to form a high performance prefabricated structural seismic system, which has important reference significance for improving the design requirements of prefabricated structures in China and popularizing the practical engineering application of prefabricated structures. The research direction and future development trends in this field are also given from the author's point of view based on our recent research work and achievements.

**Keywords:** prefabricated structures; beam-column connection; frictional damper; metallic damper; two-stage energy-dissipated

## 0 引言

预制装配式建筑最初起源于欧洲<sup>[1]</sup>,并于20世纪50年代传入我国,由于其具有施工效率高、建设周期短、施工质量有保证、绿色环保以及降低工程成本和节约投资等优点,在我国建筑工程领域中得到广泛应用。在1976年唐山大地震中,由于当时建筑耗能减振技术应用匮乏、研究相对较少,预制装配式建筑出现大量的破坏倒塌,造成了不可估量的人员伤亡和经济损失,此后预制装配式建筑在我国发展陷入了停滞状态<sup>[2]</sup>。近年来随着我国人口的老年化、人力成本的增高以及环境保护等要求,预制装配式建筑逐步重新受到重视,同时建筑耗能减振技术日益成熟,国内外学者展开了装配式建筑与耗能减振技术有效结合的大量研究<sup>[3-7]</sup>,与之对应的预制装配式相关设计规范也逐渐完善<sup>[8-9]</sup>。

结构振动控制分为主动控制、被动控制、半主动控制以及混合控制<sup>[10]</sup>,通过在结构上设置耗能减振装置,用以增大结构的刚度或阻尼,从而达到消耗地震作用或者风荷载等能量,减轻和抑制主体结构的动力反应,提高结构抵抗外界振动的能力。框架结构作为一种常用的预制装配式结构抗震体系得到了广泛关注,尤其是框架结构的梁柱节点连接方式对结构整体的抗震性能起到至关重要的作用,学者们针对各类节点展开了大量研究,验证其承载力和抗震性能<sup>[11-14]</sup>。

本文着重总结结构振动控制中的被动耗能技术装置,研究其耗能减振机理,并对当前国内外应用被动耗能减振技术的预制装配式框架结构的抗震性能的研究成果进行梳理。首次提出了一种预

制装配式梁柱耗能铰节点连接方式,总结对此节点的深化研究现状,发展和提出一种摩擦-钢板屈服两级耗能节点,并给出该节点的详细构造以及两级耗能减振机理。

## 1 常用被动耗能减振阻尼器与预制装配式结构梁柱节点的研究

现代建筑产业的发展方向和趋势为绿色化、信息化以及工业化,预制装配式建筑具有标准化设计、工厂化生产、装配化施工、一体化装修、信息化管理、智能化应用等特征,是未来发展的必由之路。预制装配式框架结构作为一种常用的建筑结构抗震体系,梁-柱节点的受力和抗震性能一定程度上限制其推广使用,而被动耗能减振技术则利用地震时耗能器先于主体结构发生屈服耗能,从而保证主体结构的安全性,将此技术应用于预制装配式结构的连接节点中提高主体结构抗震性能有着重大的发展前景,目前实际工程应用较少。如何将预制梁-柱节点与被动耗能减振技术相结合从而提高预制结构的抗震性能,国内外学者对此展开了研究。

### 1.1 摩擦阻尼器与预制装配式结构梁柱节点的结合

摩擦阻尼器作为一种应用非常广泛的位移型耗能器,最初在1980年由A.S.Pall等<sup>[15-16]</sup>提出,并在加拿大的多幢建筑中得到了应用。国内学者针对Pall型摩擦耗能阻尼器进行了试验和理论研究,并设计出了多种不同构造的摩擦阻尼器,提高了结构的抗震和耗能性能(图1)<sup>[17-20]</sup>。基本原理为通过施加一定的预紧力,利用组合构件和摩擦片组成滑动

摩擦机构,进行滑动摩擦做功,将机械能转化为热能,从而消耗输入到结构中的振动能量。摩擦阻尼器具有典型的“库仑特性”,即摩擦力与预紧力和摩擦系数正相关,其滞回曲线呈矩形,在往复荷载作用下具有良好的耗能能力以及稳定的工作性能,受荷载幅值以及加载速度影响较小,且价格低廉。常见的摩擦阻尼器有:转动型摩擦阻尼器(图2)、板式摩擦耗能阻尼器、筒式摩擦耗能阻尼器及复合型摩擦阻尼器(图3)<sup>[21-24]</sup>。

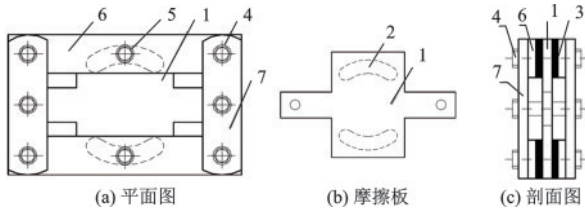


图1 改进 Pall 阻尼器<sup>[18]</sup>

Fig.1 Improved Pall damper<sup>[18]</sup>

注:1-T形板;2-滑槽;3-摩擦片;4-角螺栓;5-滑动螺栓;6-水平板;  
7-竖向板;8-垫圈

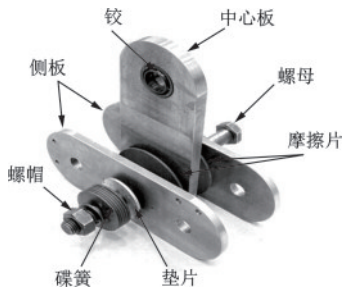


图2 转动摩擦阻尼器<sup>[21]</sup>

Fig.2 Rotational friction damper<sup>[21]</sup>

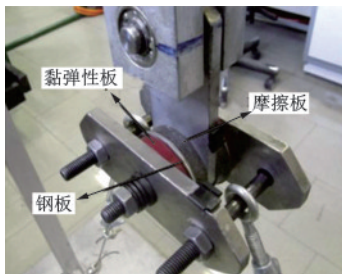


图3 转动摩擦黏弹性阻尼器<sup>[24]</sup>

Fig.3 Frictional viscoelastic damper<sup>[24]</sup>

2004年 B.G.Morgen 等<sup>[25-27]</sup>为提高后张法预应力预制混凝土框架结构抗震耗能性能,提出了在预制梁柱节点处安装弧形摩擦阻尼器的改进设计方案(图4),研究结果表明:由于在梁柱节点处设置了摩擦阻尼器,可以显著提高结构的抗震耗能性能,地震作用下减轻了主体结构的损伤,降低了结构位

移;同时由于预张力的作用使得节点具有较好的恢复能力,在外荷载作用下节点残余变形较小,M.Valente<sup>[28]</sup>在 Morgen 基础上进行了数值仿真研究,可以降低预制柱在大震下的损伤。P.Martinelli 等<sup>[29]</sup>研究了一种类似的直角转动摩擦预制梁柱节点(图5),通过在节点处设置直角转动摩擦阻尼器,提高了结构的阻尼,结构整体非线性时程分析结果表明结构顶部位移和速度,平均降低了约 37% 和 22%。A.Belleri 等<sup>[30]</sup>设计了一种三角形转动摩擦梁柱节点(图6),相比于 Martinelli 的直角节点,三角形斜撑增加了节点刚度,有利于传递横向水平荷载。M.N.Eldin 等<sup>[31]</sup>研究了一种类似三角形的滑动摩擦梁柱节点(图7),并利用了试验和非线性时程分析进行了验证,改善了结构的整体性能。上述摩擦阻尼器均独立于梁柱节点之外,作为补充耗能构件,提高了结构的抗震性能。

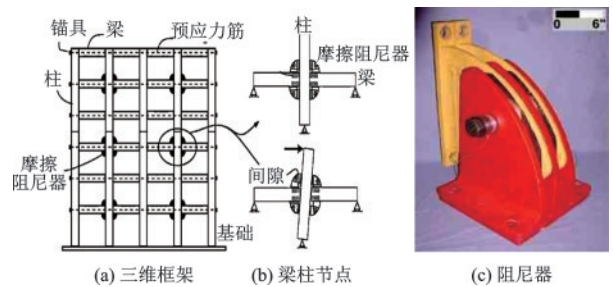


图4 弧形转动摩擦梁柱节点<sup>[27]</sup>

Fig.4 Arc rotational friction beam-column connection<sup>[27]</sup>

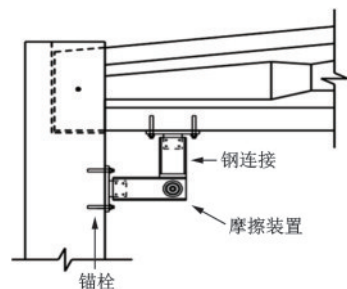


图5 直角转动摩擦梁柱节点<sup>[29]</sup>

Fig.5 Rectangular friction beam-column connection<sup>[29]</sup>

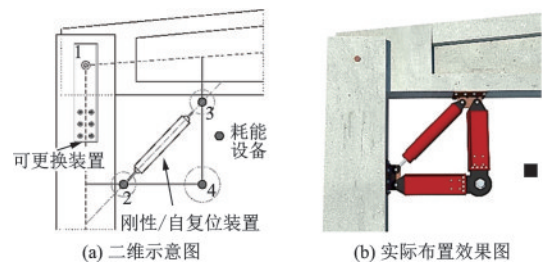


图6 三角形转动摩擦梁柱节点<sup>[30]</sup>

Fig.6 Triangular friction beam-column connection<sup>[30]</sup>



图7 三角形滑动摩擦梁柱节点<sup>[31]</sup>

Fig.7 Triangular sliding friction beam-column connection<sup>[31]</sup>

M.Wolski等<sup>[32]</sup>提出了一种在梁端下翼缘设置滑动摩擦阻尼器的预应力梁柱节点(图8),使用预应力筋代替了焊接连接,增强了节点自复位能力,摩擦阻尼器使得该节点具有稳定的耗能能力,并且在设计地震下节点保持完好。K.Deng等<sup>[33]</sup>对此节点进行了改进,在上下翼缘均设置了摩擦阻尼器,并进行了试验研究和有限元分析,得到类似结论。M.Latour等<sup>[34]</sup>研究了一种相似的梁柱节点(图9),在受到弯曲荷载时,翼缘阻尼器在拉压荷载下发生剪切变形耗能,尽管试验结果表明该节点具有较好的耗能性能,但是梁端截面与柱之间仅通过翼缘螺栓连接,导致腹板不参与受力,使得该截面的承载力和刚度不足,节点构造较不合理。郑棣<sup>[35]</sup>设计了一种翼缘摩擦阻尼预制组合梁柱节点(图10),进行了试验研究和有限元模拟,但节点受力构造有待改进,连接区截面削弱较大,可靠性有待提高。

郭彤等<sup>[36-37]</sup>设计了一种在梁腹板中心安装摩擦阻尼器的梁柱节点(图11),梁在受力时,腹板位移一般较小,摩擦阻尼器无法充分发挥其耗能能力。L.Huang等<sup>[38-39]</sup>开发了一种变阻尼的摩擦预应力梁柱节点(图12),安装在梁柱节点侧面的边缘,试验和模拟结果表明该节点可以实现变阻尼,但滞回曲

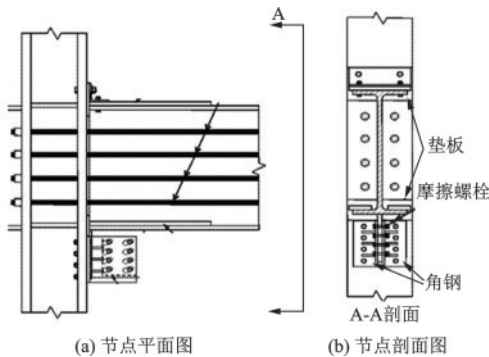


图8 弧形转动摩擦梁柱节点<sup>[32]</sup>

Fig.8 Arc rotational friction beam-column connection<sup>[32]</sup>

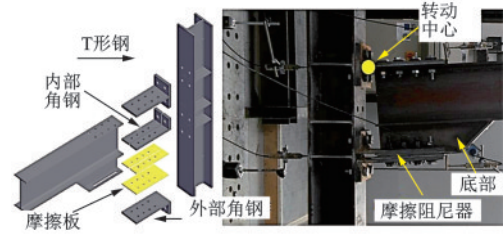


图9 弧形转动摩擦梁柱节点<sup>[34]</sup>

Fig.9 Arc rotation friction beam-column joint<sup>[34]</sup>

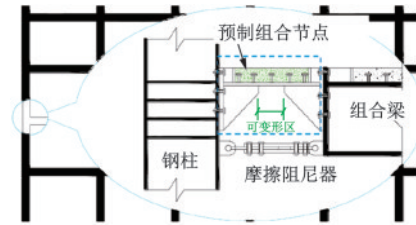


图10 新型摩擦耗能梁柱节点<sup>[35]</sup>

Fig.10 New friction energy dissipation beam-column joints<sup>[35]</sup>

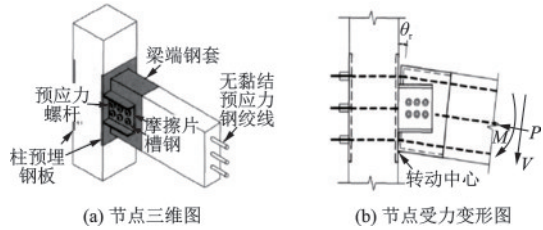


图11 腹板中心摩擦阻尼预应力梁柱节点<sup>[36]</sup>

Fig.11 Beam-Column connection with web friction damper<sup>[36]</sup>

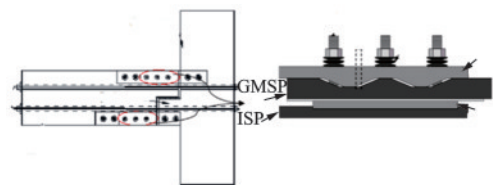


图12 腹板边缘变阻尼摩擦预应力梁柱节点<sup>[39]</sup>

Fig.12 Beam-Column connection with variable friction damper<sup>[39]</sup>

线较不饱满,耗能性能一般,同时存在梁端截面连接薄弱的问题。摩擦阻尼器要想实现耗能,必须发生一定的位移,而预应力筋则限制了节点的变形,两者之间的协调问题需进一步研究。

鲍华峰<sup>[40]</sup>研究了一种新型转动摩擦耗能梁柱节点(图13),其工作原理类似梁端塑性铰,当弯矩超过阻尼器转动摩擦弯矩时,发生转动摩擦耗能,进行了理论分析和模拟研究,表明能减轻结构地震响应,降低结构位移和剪力,未进行试验验证。杨参天等<sup>[41]</sup>研究了设置转动摩擦型干式梁-柱节点(图14)的装配式框架结构,利用非线性时程分析模拟研究了起滑弯矩对结构性能的影响,验证了该节

点的可行性。陈云等<sup>[42]</sup>设计了一种类似的装配式梁柱转动摩擦耗能节点(图15),利用低周往复加载试验研究了不同预紧力作用下节点的滞回耗能性能,滞回曲线呈现出饱满的平行四边形。上述摩擦阻尼器不仅作为阻尼器可以直接参与耗能,也是构件的组成部分,可以实现“承载-耗能”双功能的耗能组成部件。

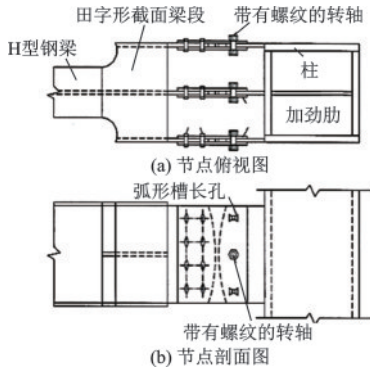


图13 转动摩擦梁柱节点<sup>[40]</sup>

Fig.13 Rotational friction damper located in beam-column connection<sup>[40]</sup>

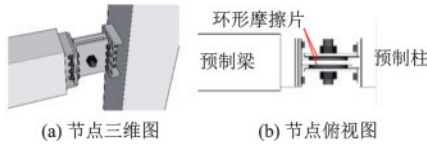


图14 转动摩擦型干式梁-柱节点<sup>[41]</sup>

Fig.14 Rotational friction beam-column connection<sup>[41]</sup>

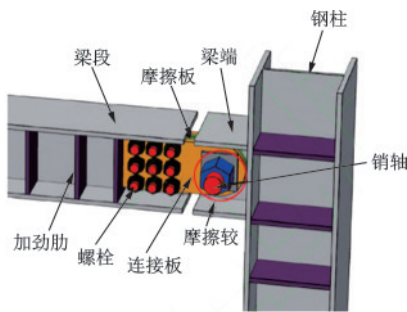


图15 梁柱转动摩擦耗能节点<sup>[42]</sup>

Fig.15 Rotational friction beam-column connection<sup>[42]</sup>

## 1.2 金属阻尼器与预制装配式结构梁柱节点的结合

金属阻尼器最早在J.M.Kelly等<sup>[43]</sup>提出,通过在主体结构中安装金属阻尼器,利用金属材料屈服时的塑性滞回变形来消耗地震能量,从而控制结构的地震反应。而后国内外学者对此类阻尼器展开了大量研究,提出了多种不同构造的金属阻尼器,其中软钢金属阻尼器应用最为广泛,研究结果表明:

金属阻尼器可以为主体结构提供一定的附加刚度和阻尼,具有良好的变形能力以及耗能能力,耗能滞回曲线呈现出纺锤形,加载方式对其耗能性能无显著影响,工作性能稳定且耐久性较好<sup>[44-50]</sup>。根据金属阻尼器的受力特点的不同,可分为拉压屈服型(防屈服支撑(图16<sup>[51]</sup>))、剪切屈服型(X形阻尼器(图17<sup>[52]</sup>)),矩形钢板阻尼器(图18<sup>[53]</sup>))、弯曲屈服型以及扭转屈服型(U形阻尼器(图19<sup>[54]</sup>)),S形阻尼器(图20<sup>[55]</sup>))等。

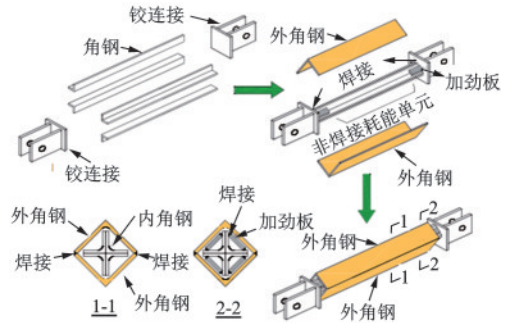


图16 防屈服支撑<sup>[51]</sup>

Fig.16 Buckling-restrained brace<sup>[51]</sup>

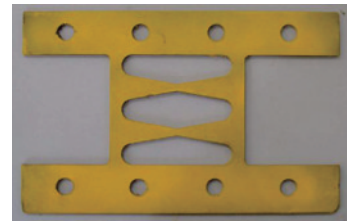


图17 X形软钢阻尼器<sup>[52]</sup>

Fig.17 X-shaped metallic damper<sup>[52]</sup>



图18 矩形钢板阻尼器<sup>[53]</sup>

Fig.18 Rectangle metallic damper<sup>[53]</sup>

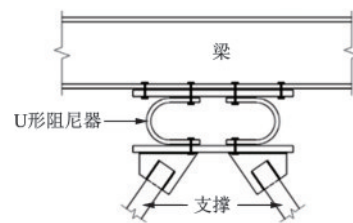


图19 U形阻尼器<sup>[54]</sup>

Fig.19 U-shaped metallic damper<sup>[54]</sup>



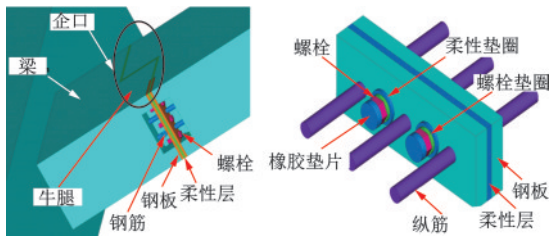


图 26 螺栓企口梁柱节点<sup>[63]</sup>

Fig.26 Bolt tongue-and-groove beam-column connection<sup>[63]</sup>

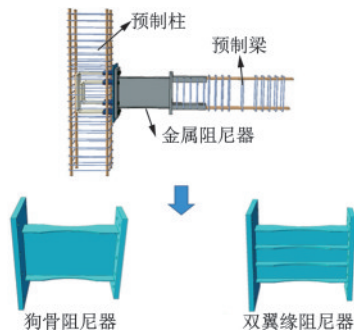


图 27 金属阻尼梁柱节点<sup>[66]</sup>

Fig.27 Beam-column connection with metallic damper<sup>[66]</sup>

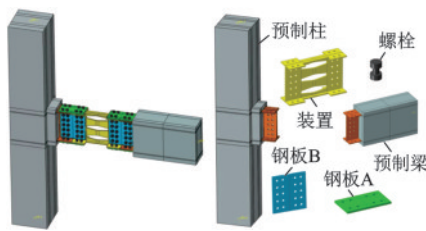


图 28 腹板开孔H型钢预制梁柱节点<sup>[67]</sup>

Fig.28 Beam-column connection with H-shaped steel<sup>[67]</sup>

孔形状、梁跨高比以及受力特征(纯剪荷载、弯剪荷载)为变量,基于试验和有限元模拟结果分析了节点的承载及耗能性能,均优于现浇梁柱节点,不足之处在于预制H型钢节点长度超过了总梁长的一半。F.Geng和Y.Li等<sup>[68-70]</sup>研究了一种预应力软钢阻尼器梁柱连接节点(图29),开展了试验研究和有限元分析,结果表明其滞回曲线呈反“S”形,耗能性能较差,独特的阻尼器形状无明显优势。L.Xie等<sup>[71]</sup>通过在预制梁柱节点上下翼缘设置金属阻尼器(图30),在弯曲荷载下,上下翼缘阻尼器拉压屈服耗能,滞回曲线饱满,耗能性能良好。

### 1.3 其他阻尼器与预制装配式结构梁柱节点的结合

T.J.Mander等<sup>[72]</sup>设计了一种梁下翼缘附加铅芯阻尼器梁柱节点(图31),M.Latour等<sup>[34]</sup>节点与此

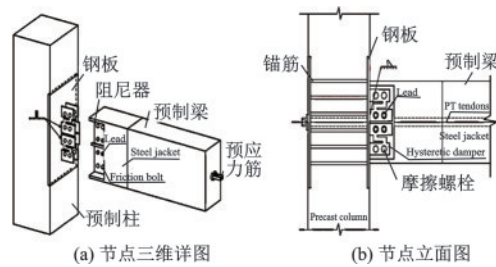


图 29 预应力软钢阻尼器梁柱节点<sup>[68]</sup>

Fig.29 Beam-column connection with mild steel damper<sup>[68]</sup>

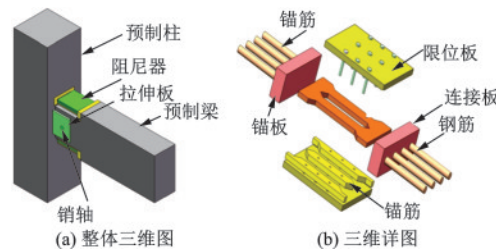


图 30 附加金属阻尼梁柱节点<sup>[71]</sup>

Fig.30 Beam-column connection with steel damper<sup>[71]</sup>

类似,两者均存在连接截面处节点薄弱,刚度不足的问题。赖伟山<sup>[73]</sup>、吴从晓等<sup>[74]</sup>研究了一款与B.G.Morgen<sup>[25]</sup>类似的预制梁柱节点(图32),不同之处其采用了扇形铅黏弹性阻尼器代替了摩擦阻尼器,开展了节点的低周往复加载试验以及整体框架的模拟分析,结果表明该阻尼器提高了结构的抗震性能。

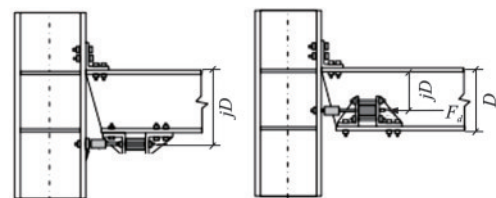


图 31 水平铅芯阻尼器梁柱节点<sup>[72]</sup>

Fig.31 Beam-column joint with lead damper<sup>[72]</sup>

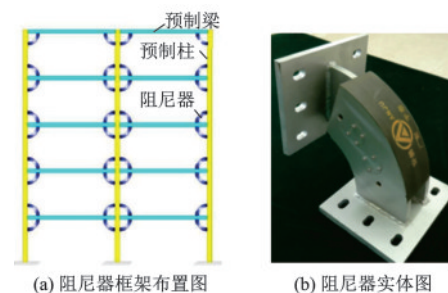


图 32 扇形铅黏弹性阻尼器梁柱节点<sup>[73]</sup>

Fig.32 Beam-column joint with lead viscoelastic damper<sup>[73]</sup>

C.Soydan等<sup>[75]</sup>利用振动台试验对预制梁柱节点有无加腋铅芯阻尼器的抗震性能进行了对比研

究(图33),结构的位移和变形均有显著降低。刘焯<sup>[76-77]</sup>研究了一款附加竹节形的金属阻尼器预制梁柱节点(图34),试验结果表明该节点滞回曲线有一定的捏缩,耗能性能较低。Z.He等<sup>[78]</sup>提出了一种装配式黏弹性减震螺栓节点(图35),设计了3个足尺梁柱节点试件,试验结果表明,与现浇节点相比,其具有较好的承载力、延性以及抗震性能。

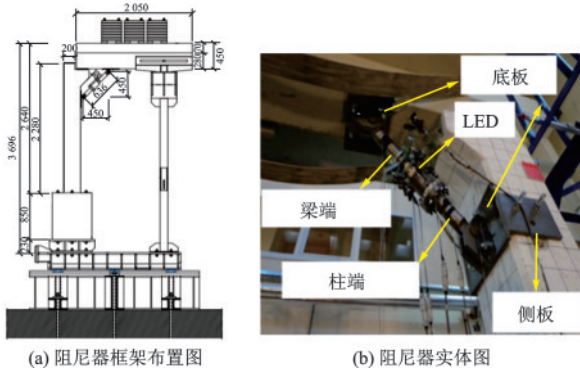


图33 加腋铅芯阻尼器梁柱节点<sup>[75]</sup>

Fig.33 Beam-column connection with lead damper<sup>[75]</sup>

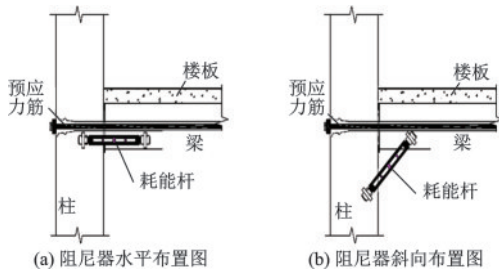


图34 竹节形阻尼器梁柱节点<sup>[76]</sup>

Fig.34 Beam-column connection with additional damper<sup>[76]</sup>

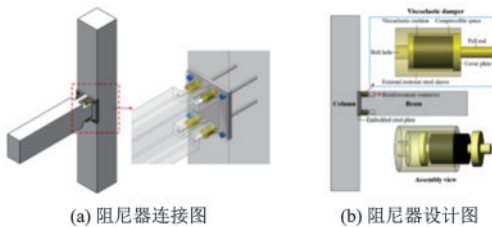


图35 装配式黏弹性减震螺栓节点<sup>[78]</sup>

Fig.35 Fabricated viscoelastic damping bolted joint<sup>[78]</sup>

## 2 预制装配式梁柱耗能节点

### 2.1 梁柱耗能较节点的研究现状

李祚华等设计了塑性可控钢质梁柱节点<sup>[79-82]</sup>(图36),并对基于此节点的装配式混凝土结构的模

块化及设计进行了研究,其研究重点侧重于节点外耗能钢板,由于耗能钢板的变形具有较好的耗能特性。但由于无翼缘钢板且腹板消弱较大,导致截面抗弯刚度和承载性能有所降低。颜桂云等亦研究了两种钢制耗能较:装配式钢质塑性可控较(图37)以及钢质往复弯曲耗能较(图38),并将两种耗能较应用于预制装配式混凝土梁柱连接,表现出良好的抗震耗能性能,主要依靠耗能钢板进行变形耗能,对“较”的构造未展开深入研究<sup>[83-88]</sup>。吴先兵等<sup>[89-90]</sup>和马哲昊等<sup>[91-92]</sup>研究了一种与上述节点类似人工消能塑性较节点,分别如图39和图40所示,其研究核心依然是外围附加耗能钢板,未对“较”自身的耗能构造进行研究。

吴刚等对两种不同类型的梁柱耗能较节点进行了研究<sup>[93-95]</sup>,分别如图41、42所示。图41所示消能减振装配式梁柱节点无翼缘板,主要依靠销轴和螺栓进行连接。图42所示刚度可控型装梁柱节点为一种半刚性梁柱节点,试验表明两种节点滞回曲线均类似Z形,有较大滑移变形,滞回曲线不饱满,耗能性能较弱。刘建武<sup>[96]</sup>亦研究了一种预制装配塑性可控节点(图43),与上述较节点构造类似,仅对其进行了有限元模拟研究,节点构造过于复杂,施工难度较大。

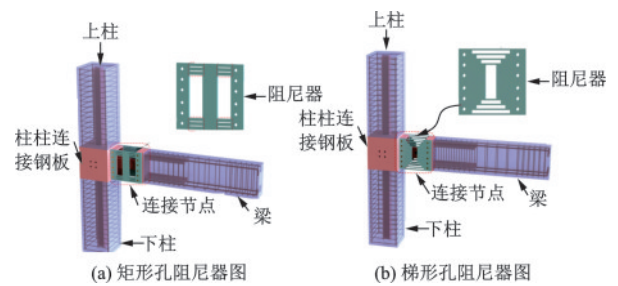


图36 塑性可控钢质梁柱节点<sup>[81-82]</sup>

Fig.36 Plastic controllable steel beam-column connection<sup>[81-82]</sup>

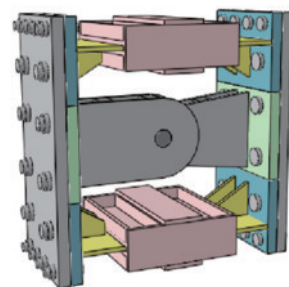


图37 装配式钢质塑性可控较<sup>[83]</sup>

Fig.37 Assembled plastic-deformation steel hinge<sup>[83]</sup>

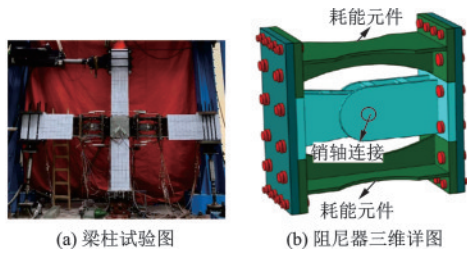


图 38 钢质往复弯曲耗能铰<sup>[84]</sup>

Fig.38 Assembly joint with a steel energy-dissipating hinge<sup>[84]</sup>

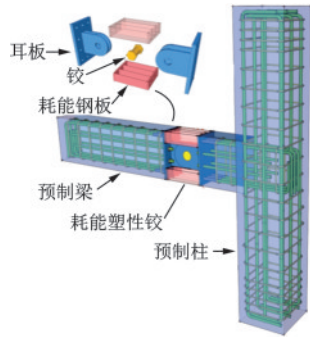


图 39 可更换消能塑性铰节点<sup>[90]</sup>

Fig.39 Replaceable controllable plastic hinge<sup>[90]</sup>

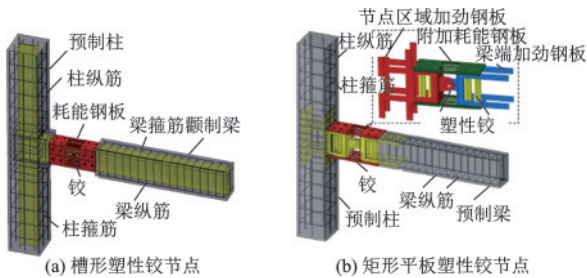


图 40 装配式消能塑性铰节点<sup>[91]</sup>

Fig.40 Prefabricated dissipative plastic hinge joint<sup>[91]</sup>

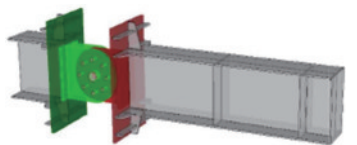


图 41 消能减振装配式梁柱节点<sup>[93]</sup>

Fig.41 Energy-dissipated beam-column connection<sup>[93]</sup>

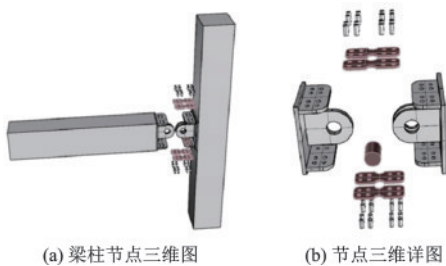


图 42 刚度可控梁柱节点<sup>[94]</sup>

Fig.42 Stiffness controllable assembled beam-column joints<sup>[94]</sup>

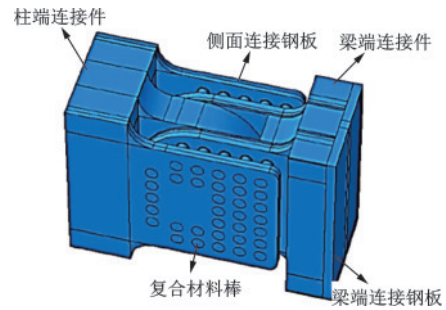


图 43 新型塑性可控节点<sup>[96]</sup>

Fig.43 Prefabricated plastic controllable joint<sup>[96]</sup>

## 2.2 预制装配式梁柱摩擦-金属屈服两级耗能节点的设计思路

根据结构动力学方程,如式(1)所示。结构质量为结构自身特性,对于特定的结构,它的质量为具体确定的参数。在被动消能减振结构中等效动荷载为外界施加的动荷载,一般为外界输入的地震动或者风荷载,具有不可控以及不可预料的特点。故为了控制结构在动荷载下的结构响应,如结构动位移、速度以及加速度,只能通过调整结构的阻尼系数和刚度系数来实现。

$M\ddot{X}(t) + C\dot{X}(t) + KX(t) = -M\ddot{x}_0(t) + F(t)$  (1)  
式中, $M$ 为结构质量; $\ddot{X}(t)$ 为结构加速度; $C$ 为阻尼系数; $\dot{X}(t)$ 为结构速度; $K$ 为刚度系数; $X(t)$ 为结构位移; $\ddot{x}_0(t)$ 为地面加速度; $F(t)$ 为等效动荷载。

振动控制系统对结构作用的实质即为等效地增加阻尼 $C$ 和(或)改变刚度 $K$ 。从式(1)可以看出:摩擦阻尼器就是增加阻尼。其优势在于弹性阶段提供摩擦阻尼力,适合于结构小震反应减振(尤其是钢筋混凝土结构),由于摩擦阻尼器不宜频繁地摩擦滑动,因此并不适用于结构风振减振。由于结构弹塑性阻尼力过大,尽管结构大震弹塑性阶段阻尼力不变,但是摩擦阻尼器在大震下起不到作用。相反,金属阻尼器作用从式(1)可以得出就是增加刚度,结构弹性阶段提供刚度 $K$ ,弹塑性阶段可以提供很大的阻尼力且极限位移适用于超大震,但是在结构弹性阶段不易也不宜提供阻尼。本文提出的摩擦-钢板屈服两级耗能节点的工作原理就是通过在在小震下提供附加阻尼、大震下增加结构刚度,从而控制结构地震动反应。两级耗能节点中摩擦铰为一种摩擦阻尼器,其作用在于小震弹性阶段提供摩擦阻尼力,具有适合于结构小震反应减振(尤其是钢筋混凝土结构)的优势;两级耗能节点中的耗

能槽钢则为一种金属阻尼器,其优点在于结构弹性阶段提供刚度 $K$ ,弹塑性阶段可以提供很大的阻尼力,适用于大震~超大震下结构的消能减振。将两级耗能节点应用于预制装配式框架结构中,实现了小震下摩擦消能减振、大震-超大震下耗能钢板屈服耗能的被动自适应耗能减振抗震结构体系。

欧进萍<sup>[97-99]</sup>在2016年首次提出了一种预制装配式结构梁柱耗能铰节点(图44),利用销轴进行节点连接,形成转动铰接机制。该耗能铰属于金属阻尼器范畴,通过拟静力以及疲劳试验,表明该节点具有良好的耗能能力以及疲劳性能,并将其应用于多高层钢结构中,静力和动力弹塑性分析表明该节点提高了结构整体的抗震性能。但是上述新型节点在“承载-耗能”功能上仍有一定的提升空间。一方面上述节点的设计是单一耗能机制,即通过梁端耗能钢板(金属阻尼器)进行屈曲耗能;另一方面金属阻尼器虽然在大震弹塑性阶段可以提供很大的阻尼力且极限位移适用于大震或超大震,但是结构在小震弹性阶段不易提供阻尼,无法实现小震-超大震下全过程耗能。本文在此基础上,结合摩擦耗能器和金属耗能器的特点,将二者并联复合一体化,发展了一种适用于预制装配式梁柱连接的摩擦-金属屈服两级耗能节点,主要由两部分组成,分别为转动摩擦耗能铰以及弯曲屈服耗能槽钢<sup>[100]</sup>,如图45所示。转动摩擦耗能铰形成铰接机制不仅承担竖向荷载,且在小变形(小震)下提供摩擦阻尼耗能,弯曲屈服耗能槽钢用于抵抗节点弯矩,并在大变形(大震或超大震)下发生塑形变形,进行屈服耗能,从而实现小-超大震下两级耗能功能。

转动摩擦耗能铰(图45)主要组成元件有内钢耳板、外钢耳板、销轴、碟簧限位板、碟簧、摩擦片、垫片以及螺帽。圆形摩擦片放置于内外钢耳板之间,其内外半径与钢耳板尺寸保持一致,利用销轴

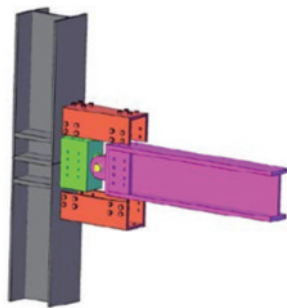


图44 耗能铰预制梁柱节点<sup>[97]</sup>

Fig.44 Beam-column connection with a prefabricated hinge<sup>[97]</sup>

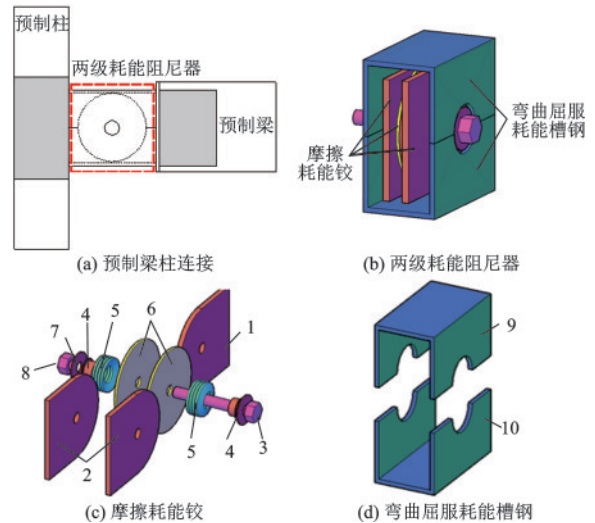


图45 梁柱摩擦-金属屈服两级耗能节点构造

Fig.45 Two-stage energy-dissipated joints

注:1-内钢耳板;2-外钢耳板;3-销轴;4-碟簧限位板;5-碟簧;6-摩擦片;7-垫片;8-螺帽;9-上槽钢;10-下槽钢

将内外钢耳板和两块圆形摩擦片连接在一起,销轴两端依次分别加入碟簧、碟簧限位板以及垫片,通过拧紧螺帽,对钢耳板和摩擦片施加预紧力,在实际受力变形时,钢耳板与摩擦片相对转动摩擦耗能,碟簧的作用在于保持预紧力,起到防止应力松弛的作用。弯曲屈服耗能槽钢包括上槽形钢板和下槽形钢板,对接形成,并在对接处进行焊接成整体的箱型截面,摩擦铰内置于耗能槽钢内部。上下槽钢由于均为低强度钢材,在受到较大的弯矩作用时,会发生屈服耗能。

### 2.3 预制装配式梁柱摩擦-金属屈服两级耗能节点的耗能机理

摩擦-金属屈服两级耗能节点在外荷载作用下发生变形,绕摩擦铰发生转动,其受力如图46所示。

当摩擦铰转动角度为 $\theta$ 时,根据变形协调原理,耗能槽钢中的上下槽形盖板变形为:

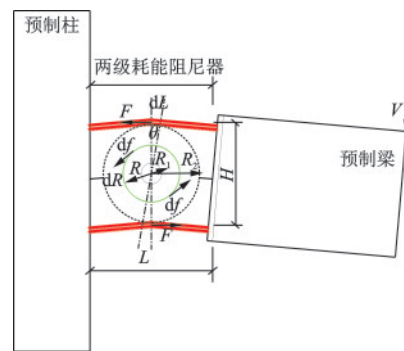


图46 摩擦-金属屈服两级耗能节点耗能分析<sup>[100]</sup>

Fig.46 Stress analysis of energy-dissipated joints<sup>[100]</sup>

$$dL = \frac{H}{2}\theta \quad (2)$$

根据金属材料受力变形计算公式,上下耗能槽钢所受拉压内力为 $F$ ,长度为 $L$ ,材料弹性模量为 $E$ ,截面面积为 $A$ ,得出:

$$dL = \frac{FL}{EA} \quad (3)$$

结合上述两式,得出:

$$\frac{H}{2}\theta = \frac{FL}{EA} \rightarrow F = \frac{H\theta EA}{2L} \quad (4)$$

摩擦耗能铰转动 $\theta$ 时,上下耗能槽钢所承受的弯矩 $M$ :

$$M = FH = \frac{H\theta EA}{2L} H = \frac{EA\theta}{2L} H^2 \quad (5)$$

从而得出在外荷载作用下,摩擦耗能铰在转动时,上下耗能槽钢变形时所累计耗能 $W$ :

$$W = \int_0^\theta M \times d\theta = \int_0^\theta \frac{EA\theta}{2L} H^2 \times d\theta = \frac{EA}{4L} H^2 \theta^2 \quad (6)$$

式中, $E$ 为耗能槽钢弹性模量; $A$ 为上下耗能槽钢截面面积; $L$ 为阻尼器的长度; $H$ 为上下耗能槽钢中心距; $\theta$ 为摩擦铰转角。

摩擦耗能铰在变形过程中,通过钢耳板与摩擦片之间摩擦,进行耗能,可根据摩擦耗能铰转动时的摩擦耗能机理,对其耗能能力进行分析计算。摩擦片的面积 $A = \pi \times (R_2^2 - R_1^2)$ ,假定摩擦铰销轴的预紧力为 $N$ ,摩擦片的应力 $\sigma = N/A$ ,钢耳板与摩擦片间的静摩擦系数为 $\mu_1$ ,滑动摩擦系数为 $\mu_2$ 。摩擦片转动时取半径 $R$ 处 $dR$ 段圆环分析,由于摩擦力与转动方向相反,假定摩擦片转动为逆时针,其 $dR$ 段圆环摩擦力为 $df$ ,且方向与为圆环切线方向。摩擦力 $df$ 是一对大小相等、方向相反的力偶,此力偶的弯矩大小 $dM$ 为 $df \times 2R$ 。

此摩擦片表面摩擦力分两种状态讨论。一种是摩擦片处于转动前的临界状态,为静摩擦力;另一种为摩擦片处于转动状态,为转动摩擦力。

(1)处于转动前的临界状态,为静摩擦力时。

$$df_1 = \mu_1 \times \sigma \times dA = \mu_1 \times \sigma \times \pi R \times dR \quad (7)$$

$$\begin{aligned} dM_1 &= df_1 \times 2R = \mu_1 \times \sigma \times \pi R \times dR \times 2R \\ &= 2\pi\mu_1\sigma R^2 dR \end{aligned} \quad (8)$$

通过积分得出,静摩擦临界状态时能抵抗弯矩 $M_1$ 为:

$$\begin{aligned} M_1 &= n \int_{R_1}^{R_2} dM_1 = n \int_{R_1}^{R_2} 2\pi\mu_1\sigma R^2 dR \\ &= \frac{2}{3} \pi n \mu_1 \sigma (R_2^3 - R_1^3) \end{aligned} \quad (9)$$

$$\begin{aligned} M_1 &= \frac{2}{3} \pi n \mu_1 \frac{N}{A} (R_2^3 - R_1^3) \\ &= \frac{2}{3} n \mu_1 \frac{N}{(R_2^2 - R_1^2)} (R_2^3 - R_1^3) \end{aligned} \quad (10)$$

此时由于钢耳板与摩擦片之间未发生转动角位移,位移量为零,故不产生摩擦耗能。

(2)当摩擦耗能铰承受的外界弯矩超过其能承受的临界弯矩时,铰的钢耳板与摩擦片之间开始发生相对转动,此阶段为滑动摩擦。利用上述临界状态的计算原理,推导出转动时摩擦片的抵抗力偶 $M_2$ 如下:

$$df_2 = \mu_2 \times \sigma \times dA = \mu_2 \times \sigma \times \pi R \times dR \quad (11)$$

$$\begin{aligned} dM_2 &= df_2 \times 2R = \mu_2 \times \sigma \times \pi R \times dR \times 2R \\ &= 2\pi\mu_2\sigma R^2 dR \end{aligned} \quad (12)$$

$$\begin{aligned} M_2 &= n \int_{R_1}^{R_2} dM_2 = n \int_{R_1}^{R_2} 2\pi\mu_2\sigma R^2 dR \\ &= \frac{2}{3} \pi n \mu_2 \sigma (R_2^3 - R_1^3) \end{aligned} \quad (13)$$

$$\begin{aligned} M_2 &= \frac{2}{3} \pi n \mu_2 \frac{N}{A} (R_2^3 - R_1^3) \\ &= \frac{2}{3} n \mu_2 \frac{N}{(R_2^2 - R_1^2)} (R_2^3 - R_1^3) \end{aligned} \quad (14)$$

假定钢耳板与摩擦片之间的相对转角为 $\theta$ ,取相对转角 $d\theta$ 为研究对象,在半径 $R$ 处 $dR$ 段圆环的转动耗能 $dW_2 = dM_2 \times d\theta$ ,利用微积分得出摩擦铰转动累积耗能 $W_2$ 为:

$$\begin{aligned} W_2 &= n \int dW = n \int dM_2 \times d\theta = n \int_0^\theta d\theta \int_{R_1}^{R_2} dM_2 \\ &= \frac{2}{3} n \mu_2 \frac{N}{(R_2^2 - R_1^2)} (R_2^3 - R_1^3) \theta \end{aligned} \quad (15)$$

式中, $\mu_1$ 为钢耳板与摩擦片间的静摩擦系数; $\mu_2$ 为钢耳板与摩擦片间的滑动摩擦系数; $N$ 为销轴预紧力; $R_1$ 为摩擦铰内径; $R_2$ 为摩擦铰外径; $\theta$ 为摩擦铰转角; $n$ 为摩擦铰摩擦面数量。

$$\begin{aligned} \frac{M}{M_2} &= \frac{EA\theta H^2/2L}{\frac{2}{3} n \mu_2 \frac{N}{(R_2^2 - R_1^2)} (R_2^3 - R_1^3)} \\ &= \frac{3EA\theta H^2 (R_2^2 - R_1^2)}{4n\mu_2 LN (R_2^3 - R_1^3)} \end{aligned} \quad (16)$$

$$\begin{aligned} \frac{W}{W_2} &= \frac{EAH^2\theta^2/4L}{\frac{2}{3} n \mu_2 \frac{N}{(R_2^2 - R_1^2)} (R_2^3 - R_1^3) \theta} \\ &= \frac{3EA\theta H^2 (R_2^2 - R_1^2)}{8n\mu_2 LN (R_2^3 - R_1^3)} \end{aligned} \quad (17)$$

从式(17)得出,当结构两级耗能阻尼器处的铰

节点变形位移角较小时,摩擦铰耗能占比较大;位移角较大时,则耗能槽钢耗能占比相对提高。从而满足在弹性阶段时,主要由摩擦铰转动摩擦耗能,当阻尼器发生塑性变形时,上下耗能槽钢开始变形屈服耗能,实现两级耗能功能要求。同时加大预紧力以及提高摩擦系数,均有利于提高摩擦铰的耗能能力。

### 3 结论及展望

#### 3.1 结论

总结了目前常用的结构被动耗能减振技术,由于传统的装配式结构抗震性能较差,国内外学者展开了大量的研究将传统装配式结构与耗能减振技术有效的结合提高装配式结构的抗震性能,对此进行了分类归纳,同时针对本文提出的预制梁柱耗能铰节点的研究现状进行了梳理,提出了一种预制装配式梁柱摩擦-金属屈服两级耗能节点,主要结论如下:

(1)被动耗能减振技术可以有效地提高结构的抗震性能,针对常用的位移型被动耗能阻尼器进行了归纳分析,总结了摩擦阻尼器以及金属阻尼器的耗能机理以及工作特点,具有耗能性能稳定、构造简单以及造价等方面的优势。

(2)被动耗能减振技术与预制装配式结构可以进行有效的结合,从而提高结构的抗震性能,有利于预制结构在中高地地震烈度地区的推广使用,重点对预制装配式框架结构的耗能梁柱节点进行了梳理,尽管诸多学者开发了多种不同类型的耗能节点,但是实际工程的应用有待进一步推广。

(3)本课题组提出了一种预制梁柱耗能铰节点,开展了理论分析、试验研究以及数值模拟,验证了该节点的有效性以及可靠性,国内诸多学者在此基础上进行了深化研究,设计了多种耗能铰节点,但是主要集中于耗能铰外侧的耗能钢板,而未对“铰”自身的特性进行研究。

(4)结合摩擦阻尼器以及金属阻尼器的特点,提出了一种适用于预制梁柱的摩擦-金属屈服两级耗能节点,给出了该节点的详细构造,由转动摩擦耗能铰以及弯曲屈服耗能槽钢两部分组成,并进行了变形耗能分析,可以实现小变形(小震)~大变形(大震或超大震)下的两级耗能功能。

#### 3.2 展望

(1)预制装配式结构的连接问题,是影响其抗震性能的重要因素,将连接部位的阻尼器设计成既是受力构件又是耗能构件是一种发展趋势,可以有效地控制失效模式。此“承载-耗能”双功能阻尼器应具有在正常使用工况下起到连接各预制构件的功能,又可以在风振或地震中起到耗能减振的作用,满足承载以及被动系统控制的要求。

(2)隔震减振技术与预制装配式结构形成高性能装配建筑结构抗震体系,耗能减振技术作为一种成熟的结构消能减振技术在预制装配式结构的实际工程应用有待深入系统的研究。

(3)单一耗能形式的阻尼器其耗能能力有限,如何根据各种阻尼器的特性将多重不同形式的阻尼器进行组合,从而开发出耗能性能更强、适用性更广、稳定性更好的阻尼器,亦是未来的研究方向。

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